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WHOLESALE REPLENISHMENT MODELS:
MODEL EVALUATION

by

Roger Elliot Hammer, Jr.

June 1987

Thesis Advisor: Alan W. McMasters

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This thesis analyzes a new wholesale level repairables replenishment model proposed for implementation by the U. S. Navy. The new model uses the total investment level as its measure of effectiveness with a mean supply response time (MSRT) goal as a constraint. In addition, the new model requires that procurement and repair order quantities be specified as input parameters. The importance of the model is that it relates resources to readiness, an area of primary concern to Congress and the Department of Defense. Tests with actual data were conducted between the current Navy repairables model and the new model. The results of these tests indicate that the new model would consistently out-perform the current model for investment levels and system material availability (SMA).

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Wholesale Replenishment Models: Model Evaluation

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis analyzes a new wholesale level repairables replenishment model proposed for implementation by the U.S. Navy. The new model uses the total investment level as its measure of effectiveness with a mean supply response time (MSRT) goal as a constraint. In addition, the new model requires that procurement and repair order quantities be specified as input parameters. The importance of the model is that it relates resources to readiness, an area of primary concern to Congress and the Department of Defense. Tests with actual data were conducted between the current Navy repairables model and the new model. The results of these tests indicate that the new model would consistently outperform the current model for investment levels and system material availability (SMA).

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I. INTRODUCTION

A. BACKGROUND

In early 1977, the Naval Supply Systems Command (NAVSUP) began planning for a major project to replace all ADP system hardware and software at the Navy's two inventory control points (ICP's). Although the primary objective of this resystemization effort, known as Project Resolicitation, was to upgrade obsolete computer hardware at the Aviation Supply Office (ASO) in Philadelphia, Pennsylvania and the Ships Parts Control Center (SPCC) in Mechanicsburg, Pennsylvania, it also provided the opportunity to reevaluate the existing peacetime wholesale level inventory models used at these activities. [Refs.1,2,3]

In the spring of 1982, NAVSUP requested the Naval Postgraduate School to evaluate the existing wholesale provisioning and replenishment models for secondary items and make recommendations for improvements or changes. Throughout 1982 and 1983, Richards and McMasters investigated the question of an appropriate wholesale provisioning model because improvements to the existing models had been given top priority by NAVSUP planners. They concluded that a new model should be developed around an objective function which directly relates resources to combat readiness as Congress and the Department of Defense were placing considerable emphasis on this relationship. [Refs.2,3]

The new wholesale provisioning model proposed by Richards and McMasters was accepted for implementation by the Navy in December 1984. This model minimizes the aggregate mean supply response time (MSRT) for the total population of

repair parts purchased for a new weapon system subject to an overall budget constraint. The MSRT model was selected over other proposed models because of its direct relationship to operational availability (A_o) as defined by the Department of Defense and the fact that this is the only variable in the definition that the supply system can affect. [Refs.2,4]

Following development of the provisioning model, attention shifted to the wholesale repairables replenishment model. Repairables, or more specifically depot level repairables (DLR's), presently account for over 80 percent of the estimated $28.0 billion wholesale inventories managed by ASO and SPCC [Refs.5,6]. As such, they are the focus of considerable management attention both within the Navy and the Department of Defense. DLR's are categorized as relatively high value components which have been determined to be more economical to repair than to replace when they fail in use [Ref.7].

In order to provide a smooth transition from the initially provisioned inventory to the follow-on replenishment process, it was logical that the new repairables model be developed using a theoretical framework similar to that used in the new provisioning model. During 1984, Apple, working with Richards and McMasters, developed the first formulation for a new wholesale repairables replenishment model which used minimization of MSRT in the objective function [Ref.8]. The Apple model was a multi-echelon model which attempted to incorporate the effects of not stocking a particular item at the shipboard level. As such, this model could not be easily implemented at the wholesale level because the ICP's do not currently maintain precise information about the range and depth of repair parts stocked by fleet operating units.

Throughout 1985 and 1986, both Gormly and Pearsall, also students of Richards and McMasters, continued work on the repairables model developed by Apple. Gormly converted Apple's multi-echelon model to an aggregate demand model which could be used at the ICP level with the existing ICP demand forecasting programs [Ref.9]. Pearsall investigated the potential impact of the Gormly MSRT model on ICP procurement workload and tested the model with selected real world data provided from ASO and SPCC data bases [Ref.10].

B. OBJECTIVES

The primary objective of this thesis is to compare the theoretical performance of the wholesale repairables model currently used by the ICP's against that of the Gormly aggregate demand MSRT model. The performance measures used for this comparison are total investment in wholesale stock and system material availability (SMA). Secondly, this thesis attempts to verify some of the underlying assumptions for the MSRT model and examine the effects of various stocking, repair and procurement policies on mean supply response time and material availability through the use of inventory simulation.

C. PREVIEW

Chapter II of this thesis provides an overview of the Navy Supply System including sections on the Navy Stock Fund, the repairables system and supply system performance measures. This is followed by a detailed presentation of the Gormly aggregate demand MSRT model and the current ICP integrated repairables model in Chapter III. Chapter IV discusses results from the performance comparison tests

conducted using actual inventory management data provided by ASO and SPCC. Chapter V describes the repairables model simulation programmed for the MSRT model and discusses results of simulation test runs. The final chapter summarizes results of research conducted during the first half of 1987 for the MSRT repairables model and provides recommendations for areas requiring additional study.

II. THE NAVY SUPPLY SYSTEM

The purpose of this chapter is to acquaint the reader with the current management organization and policies of the Naval Logistics and Supply Systems. The first section provides an overview of the present Navy logistics organization and discusses the roles of the major logistics commands. This section is followed by a more complete discussion of the military supply system and the roles and responsibilites of activities under the cognizance of the Commander, Naval Supply Systems Command (NAVSUP). The second half of the chapter includes sections on the Navy Stock Fund, the Repairables System and Supply System Performance Measures. These sections are included to provide the reader with a better understanding of factors influencing development of the new repairables inventory model presented in Chapter III.

A. THE NAVY LOGISTICS ORGANIZATION

Within the Navy, primary responsibility for logistics support of operating forces rests with the Chief of Naval Operations (CNO). As the senior military officer in the Navy, the CNO is responsible for planning and determining all material support needs of operating forces including equipment, weapon systems, materials, supplies, facilities, maintenance and supporting services [Ref.11]. Under the Chief of Naval Operations, there are five major systems commands assigned logistics management responsibilities: the Naval Air Systems Command (NAVAIR), Naval Sea Systems Command (NAVSEA), Space and Naval Warfare Systems Command (SPAWAR),

the Naval Facilities Engineering Command (NAVFAC) and the Naval Supply Systems Command (NAVSUP). Until 1985, the five systems commands were part of the Naval Material Command (NAVMAT) under the administrative control of the Chief of Naval Material. The Naval Material Command was dissolved in 1985 by the Secretary of the Navy, and NAVMAT administrative responsibilities were assumed by the Office of the Secretary of the Navy (SECNAV), the Office of the CNO (OPNAV) and the Systems Commands.

Three of these commands, NAVAIR, NAVSEA and SPAWAR, known as Hardware Systems Commands (HSC's), have overall responsibility for acquisition and maintenance of weapon systems and major end items used by the Navy's operating forces. The HSC's act as the central technical authorities on all matters relating to support and maintenance of weapon systems for which they are responsible. Additionally, the HSC's have inventory management responsibility for selected secondary items of supply stocked within the Naval Supply System. [Refs. 7, 11]

NAVFAC performs a similar function for the facilities requirements of the Navy shore establishment. NAVFAC has responsibility for administration of the military construction program, shore facilities planning and maintenance, and material support for construction and transportation equipment. [Ref. 11]

NAVSUP, as the lead agency responsible for coordination of supply support for all operating forces and shore activities, performs a wide variety of functions including administration of the Naval Supply System, the Navy Resale Program, publications and printing, the Navy Stock Fund, the field contracting system and the Navy Transportation System. Additionally, NAVSUP administers the Navy Food Service

Program and exercises management control over all Navy material handling equipment (MHE) and special clothing. [Ref.11]

B. SUPPLY SYSTEM OVERVIEW

Conceptually, the Navy Supply System is described as a multi-echelon system in which responsibility for inventory management of secondary items of supply is cooperative effort involving a large number of activities operating on the local, regional and national/worldwide level. The majority of these are end-use consumer activities (ships, aviation squadrons and shore facilities) which stock material inventories exclusively for their own consumption. The remainder are comprised of regional and national stock points and inventory control points operated by the Navy, the Defense Logistics Agency, the General Services Administration and the other military services. Within the the larger DOD Supply System, approximately 4 million items of supply valued at over $100 billion are stocked in support of operating forces. Of these, the Navy uses approximately half or 2 million items [Ref.11].

The Naval Supply System is concerned exclusively with inventory management of secondary items of supply, as opposed to complete weapon systems or principal end items. Secondary items are by definition "Consumable and repairable items and those end items not classified as principal end items." [Ref.12] Seoondary item requirements are determined by the inventory control point (ICP) which has been assigned management responsibility for the item and are based on either observed/estimated demand or non-demand based insurance levels. Item attrition is based on normal in-

service wearout or consumption rates. Procurement of secondary items is financed with either stock funds or appropriated/investment funds depending on such factors as unit price, expected item life and item recoverability. Budget formulations for secondary items are based upon standard levels setting techniques and stratification projections. Finally, issues to end-use activities are subject to established allowances determined by the ICP's but are not usually restricted if the activity has a valid requirement for the item. [Ref.13]

In contrast, a principal end item is defined as "A final combination of end products, component parts and/or material which is ready for its intended use (e.g. ship, aircraft, truck, mobile machine shop, etc.)." [Ref.12] Principal end items are specifically designated as such by the CNO, with responsibility for requirements planning and procurement delegated to the Systems Commands. Budget formulations for principal end items are accomplished separately from secondary items through material planning studies, cost benefit analysis and principle item stratifications. Procurements are financed exclusively with appropriated/investment funds under specific programs approved by Congress. Principal item attrition is based solely on major/total destruction, intended destructive use, or planned retirement. Issues to end-use activities are strictly limited to established allowances or by special authorization from the appropriate Systems Command. [Ref.13]

There are three levels of inventory managed within the Navy Supply System: Retail-Consumer, Retail-Intermediate and Wholesale [Ref.12]. As already indicated, Retail Consumer inventories are held by operating units and shore facilities not having supply support as a primary mission. Only those

items of supply required to support the primary mission of the unit are carried in stock at the Retail Consumer level. Material held at the organizational level includes both demand based items, and non-demand based insurance items, which are stocked to reduce the probability of extended down time for mission essential equipment.

The Retail Intermediate Level, or first echelon of resupply within the Navy, includes inventories stocked by ships of the Mobile Logistics Support Force (fleet issue ships, tenders, repair ships), Naval Supply Depots (NSD's) located overseas, Naval Supply Centers (NSC's) located in the United States, selected shore activities having special missions (e.g., Naval Shipyards) or other activities located close to fleet customers (e.g., Naval Air Stations). Mobile Logistics Support Force (MLSF) ships and overseas depots have primary responsibility for supply support of deployed operating units and shore activities located overseas. Regional supply centers and Naval Air Stations (NAS's) located in the United States are responsible for supply support of operating units and shore activities located in their designated geographical areas. Naval Shipyards (NSY's) stock retail inventories exclusively for their own needs. [Ref.7]

The Wholesale Level, or second echelon of resupply within the Navy, is oriented toward providing supply support at the national and worldwide level as opposed to the regional and local level. Physical inventories of wholesale material are stocked at six Defense Supply Depots and eleven GSA Supply Centers located throughout the United States, and at the seven Naval Supply Centers (in addition to their Retail Intermediate inventories). Under the DOD Integrated Material

Management Program implemented for the wholesale level, each item of supply is assigned to a single inventory manager so that no two ICP's have responsibility for the same item of supply. [Ref.7]

Within the Navy, the Aviation Supply Office (ASO) and the Ships Parts Control Center (SPCC) are the two inventory control points assigned wholesale level inventory management responsibilities. The Navy ICP's have two primary functions relative to the management of secondary items of supply: supply support and program support. The supply support function is commodity oriented and involves inventory management of secondary items used exclusively by the Navy, as well as some items used by the other services. Supply support functions include inventory levels setting, material identification and cataloging, consolidated allowance list preparation, maintenance of item planning and technical data, and arrangements for financing of system stocks. [Ref.7]

Program support is weapon system oriented as opposed to commodity oriented and involves coordination of all supply support arrangements for weapon systems and equipment in the Navy inventory. Program support functions include secondary item cataloging, initial provisioning, allowance list preparation, arrangements for material repair and replenishment, and monitoring the overall logistic support status of assigned equipment and systems [Ref.7]. As many items of supply required for support of Navy systems at the wholesale level are managed by non-Navy activities, the program support manager is responsible for ensuring that these activities procure sufficient stock to meet the Navy's planned requirements when new weapon systems are fielded.

C. THE NAVY STOCK FUND

The Navy Stock Fund (NSF) is a working capital revolving fund established by Congress for purchase of secondary items of supply stocked within the Navy Supply System. Items of supply purchased with NSF money are held in suspense in the Navy Stock Account (NSA) on the inventory records of Navy stock points until they are issued or "purchased" by an end use activity. When NSA stock is issued or "sold" by a stock point, the Navy Stock Fund is reimbursed for the cost of the material with funds transferred from the Operation and Maintenance (O&M) appropriation of the requisitioning activity. Although the ratio of materials to cash in the Navy Stock Fund is constantly changing over time, the fund maintains a relatively constant total asset value. This total asset value of money and material is often referred to as the "corpus" or body. [Refs.7,14]

In order to recover all costs associated with inventory management of supplies purchased with stock fund money, a surcharge is added to the price of each item issued from stock. The surcharge is designed to reimburse the fund for material losses due to damage, obsolescence or physical loss; transportation charges for material moving between stock points and to customers; and anticipated price increases for material purchased from commercial vendors. [Refs.7,14]

Administration of the Navy Stock Fund is the responsibility of NAVSUP. NAVSUP, in turn, has assigned management control for NSF money to the two Navy ICP's, ASO and SPCC, and to the Navy Retail Office (NRO) at the Fleet Material Support Office (FMSO) located in Mechanicsburg, Pennsylvania. ASO and SPCC use stock fund money to purchase new repair parts and consumables directly from manufacturers and to fund repair of depot level repairables (DLR's) at both

Navy and commercial repair activities. Wholesale material purchased by the Navy ICP's is "pushed" to designated stock points where it is held in inventory along with the activity's own retail stock. [Ref.7]

The Navy Retail Office allocates NSF money to Retail Stock Points for purchase of materials and supplies stocked for eventual resale to their own customers. Sources of supply for NSA material purchased by Retail Stock Points include both DLA and GSA wholesale level activities, ASO and SPCC, as well as commercial vendors. Material purchased from wholesale level activities for stocking at the retail level is "pulled" from the wholesale system by registering customer demands with the inventory control points. [Ref.7]

Until 1981, all depot level repairables (DLR's), due to their relatively high unit cost, were classified as investment items and were procured and repaired with funds appropriated annually by Congress. As system stocks of DLR's had already been paid for with investment funds, the customers' operating budgets were not charged when a repairable was issued from system stocks. On 1 April 1981, all non-aviation DLR's managed by SPCC were capitalized into the Navy Stock Fund under a pilot program designed to improve system-wide asset management of repairables [Ref.7]. The primary reason for transferring DLR's to the stock fund was to provide increased funding flexibility to repair or reprocure system assets as required without having to go through the lengthy annual budget process. The pilot program was so successful that a major portion of aviation DLR's managed by ASO were also transferred to the Navy Stock Fund on 1 April 1985 [Refs. 5,7].

In order to reimburse the stock fund for the cost of repairs and replenishments for DLR's, a dual pricing system was implemented in which the customer is charged either a reduced "repair price" or full reprocurement price depending on whether a repairable carcass is turned-in to the supply system. The new pricing system has had the added benefit of improving management of repairable assets at the user level as customers are now charged the full reprocurement price for failing to turn items in promptly. [Ref.7]

D. THE REPAIRABLES SYSTEM

Within the Navy, a system component is designated as a repairable if its repair cost is less than one hundred percent of its replacement cost and/or its repair time is less than its procurement lead time [Ref.10]. A component is initially designated as a repairable during the design phase of development for a new weapon system through a process known as level of repair analysis (LORA). The LORA process not only determines whether a system component will be a repairable, but also the level of maintenance at which it will be repaired. An item designated as a repairable continues to be managed separately during initial provisioning for the new weapon system and subsequently during the repair and reprocurement cycles until it no longer meets the criteria for being a repairable or the weapons system is phased out.

There are three levels of maintenance at which repair action may occur: (1) the organizational level (i.e., a ship); (2) the intermediate level (i.e., tender, aircraft carrier or shore intermediate maintenance activity); and the depot level (i.e., Naval Shipyard, Naval Air Rework Facility or commercial repair activity). Repair of Navy depot level

repairables (DLR's) is centrally managed at the wholesale level by the two ICP's: ASO and SPCC. Figure 2.1 illustrates the flow of transactions and movement of material for depot level repairables. [Ref.7]

The cycle begins when a customer submits a requisition (demand) for a DLR to the nearest stock point (e.g., NSC, NAS). In the normal situation, the customer will also ship a failed component to the stock point within a few days following submission of the requisition. If the requested item is available for issue at the stock point, it is shipped directly to the requisitioner. Otherwise, the requisition is referred to the inventory manager at the ICP having responsibility the material. If the item is available at another stock point, the inventory manager refers the requisition to that activity for issue. Once the item has been shipped from a stock point, the transaction is reported to the cognizant ICP by means of a transaction item report (TIR). If a ready-for-issue (RFI) component is not available within the system, the demand will be recorded as a backorder against material which is due in from repair or procurement.

At the wholesale level, the inventory manager's primary responsibility is to ensure that an adequate number of units, both RFI and not-ready-for issue (NRFI), are available within the system to fill programmed requirements and expected future demands from customers. This is no easy task given the rapid advancements in weapon systems technology which often make repair parts obsolete in a relatively short period of time. The repairables management problem is further complicated by the fact that procurement lead times for these high dollar value items often exceed four years. Consequently, the inventory manager must constantly be alert

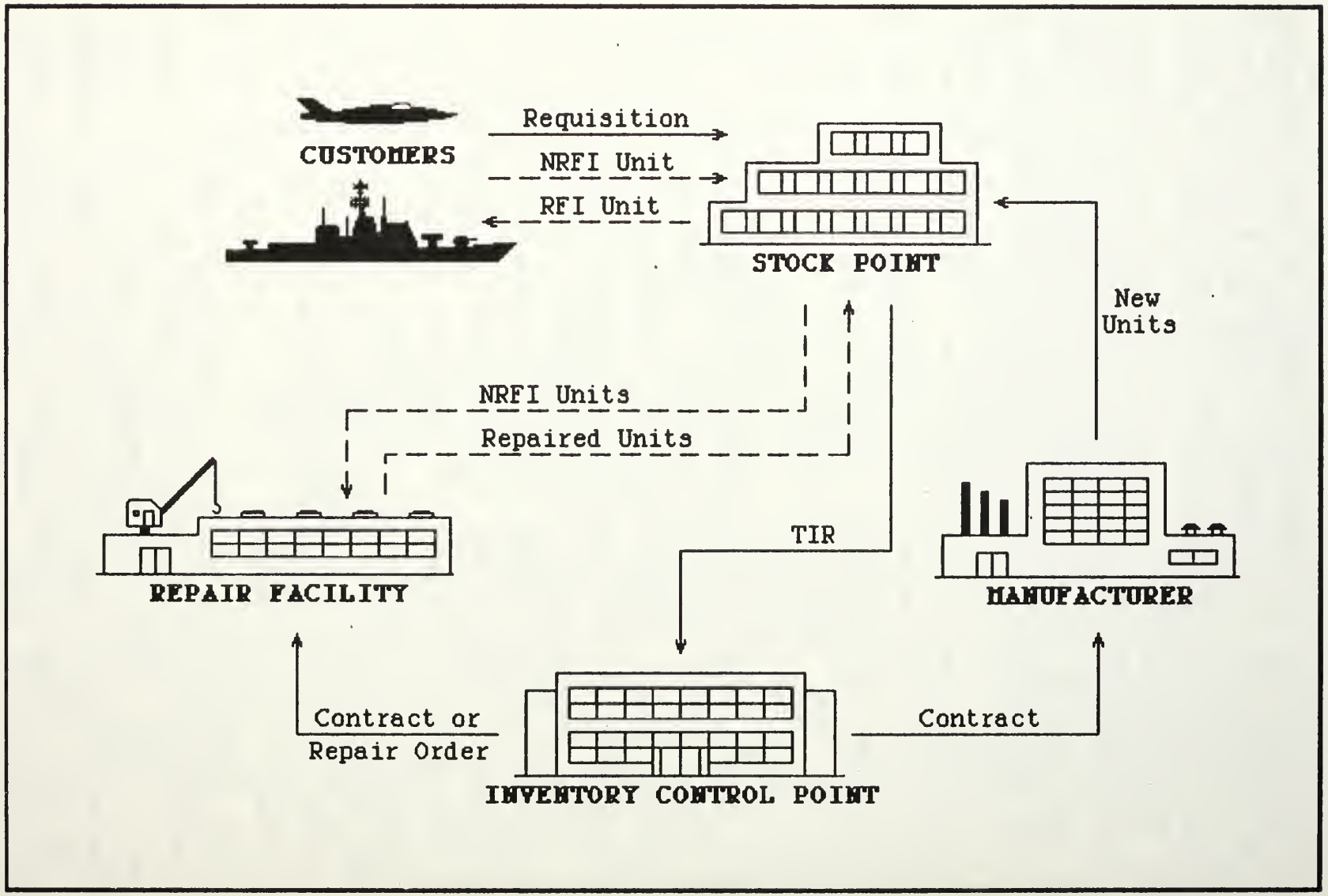

Figure 2.1 Depot Level Repairables Inventory System

to changes in demand patterns which would result in either an overstockage situation or critical shortage of material.

At present, the ICP's major areas of concern are carcass tracking and repair turnaround times. Recently, a new Repairables Management Data System has been implemented at ASO and SPCC to maintain more positive control of repairable assets moving through the system and to monitor repair progress at designated overhaul points (DOP's). The purpose of the system is to reduce repair turnaround times and improve carcass return rates [Ref.7] Recent discussions with SPCC repairables managers indicate repair turnaround times for non-aviation DLR's have been reduced by 44 percent over the past 4 years and now average just over 120 days [Ref.15].

While repair management occupies the majority of the inventory manager's time, he must still actively monitor system attritions and promptly initiate reprocurement action with the manufacturer when a shortfall is projected. Currently, the Supply Demand Review (SDR) application is used at the ICP's to identify candidates for reprocurement. SDR is part of a larger group of computerized inventory modeling applications and files collectively known as the Uniform Inventory Control Program (UICP). As indicated above, long procurement leadtimes for many repairables coupled with low attrition rates make procurement forecasting more an art than a science. Often a manufacturer for a particular item has already ceased production and would have to expend considerable effort to reconfigure his current production line to make the small number of items required by the Navy.

E. SUPPLY SYSTEM PERFORMANCE MEASURES

In order to ensure the military's operating forces maintain a high degree of material readiness, the Secretary

of Defense, in consultation with the military services and the Defense Logistics Agency has established uniform inventory management policies and minimum performance goals for both the wholesale and retail levels of supply. The CNO has also established minimum performance goals for weapon system operational availability which includes supply support as a key parameter. The following is a detailed discussion of the measures of performance used by the Naval Supply System to guage mission effectiveness. Definitions and formulas in this section are taken from NAVSUP Publication 553 [Ref.7] unless otherwise indicated.

Performance measures used by the supply system fall into two major interrelated categories: material availability and supply response time (or delay time). Material availability measures include System Material Availability (SMA) or Gross Availability, computed at the wholesale level; and Gross and Net Availability, computed at the Retail Level. Supply response time measures include Average Days Delay (ADD), Average Days Delay for Delayed (backordered) Requisitions (ADDDR) and Average Customer Wait Time (ACWT), also known as Mean Supply Response Time (MSRT).

SMA (or Gross Wholesale Availability) is defined as the percentage of customer requisitions received at the wholesale level which are filled from on hand stock. SMA can be computed as:

$$\text{SMA}(\%) \equiv 100 \left[1 - \frac{\text{Backorders Established}}{\text{Total Demands at the Wholesale Level}} \right].$$

The SMA goal established by the CNO for the wholesale level is presently 85 percent [Ref.12].

Both Gross Availability and Net Availability are performance measures established by DOD for the Retail Intermediate and Consumer Levels of supply. Gross Availability, also called Point of Entry (POE) effectiveness at Navy stock points, is defined as the percentage of total demands for both stocked and non-stocked items that are satisfied from on hand inventory. Gross Availability at the retail level is computed in the same manner as SMA is computed for the wholesale level. The Gross Availability goal for the Retail Intermediate Level is presently set at 70 percent. [Ref.12] At the Retail Consumer Level, Gross Availability goals are 65 percent for ships and shore activities receiving intermediate level support, and 75 percent for aviation units [Ref.12].

Net Availability is the percentage of total of demands received for stocked items that are filled from stock at the supplying activity:

$$\text{Net Availability}(\%) = 100 \left[\frac{\text{Demands Filled for Stocked Items}}{\text{Total Demands for Stocked Items}} \right].$$

The Net Availability goal for both Retail Intermediate and Consumer activities is currently set at 85 percent [Ref.12].

ADD is a measure of how long it takes to fill requisition received at the wholesale level from available system stock. As the ICP's do not presently collect times required to fill individual requisitions, the ADD calculation is approximated by:

$$\text{ADD} = \frac{\text{Backorders at the End of the Month}}{\text{Requisitions Processed During the Month}}.$$

ADDDR attempts to measure how long it takes to fill a backordered requisition. ADDDR is computed using the following approximation:

$$\text{ADDDR} = \frac{\text{Backorders at the End of the Month}}{\text{Backorders Established During the Month}} .$$

Average Customer Wait Time (ACWT) is defined as the average time, in days, required to fill a customer demand regardless of whether or not the item is stocked in the supply system. For the Navy, the CNO has established an ACWT goal of 125 hours for critical maintenance requirements requisitioned by end-use activities located in the continental United States (CONUS) and 135 hours for activities outside the United States (OUTCONUS) [Ref.12]. The system-wide ACWT goal of 125 hours is computed by weighting the supply response time goals established for each of the three levels of supply by their respective material availability goals as shown in Figure 2.2. [Ref. 12]

Mean Supply Response Time (MSRT) as defined in NAVMATINST 3000.2 is a weighted average of supply response times from organizational level stocks and from the supply system. This definition is analogous to the definition for ACWT. The importance of MSRT as a measure of supply system performance is demonstrated through the following discussion of Operational Availability, which is the official measure of weapon system performance for the Navy. [Ref.4]

Operational Availability (A_o) represents the expected percentage of time that a weapon system or equipment will be ready to perform satisfactorily in an operating environment [Ref.4]. Alternatively, A_o is also defined as "the probability that a weapon system or equipment, when used under stated operating conditions in an actual operating

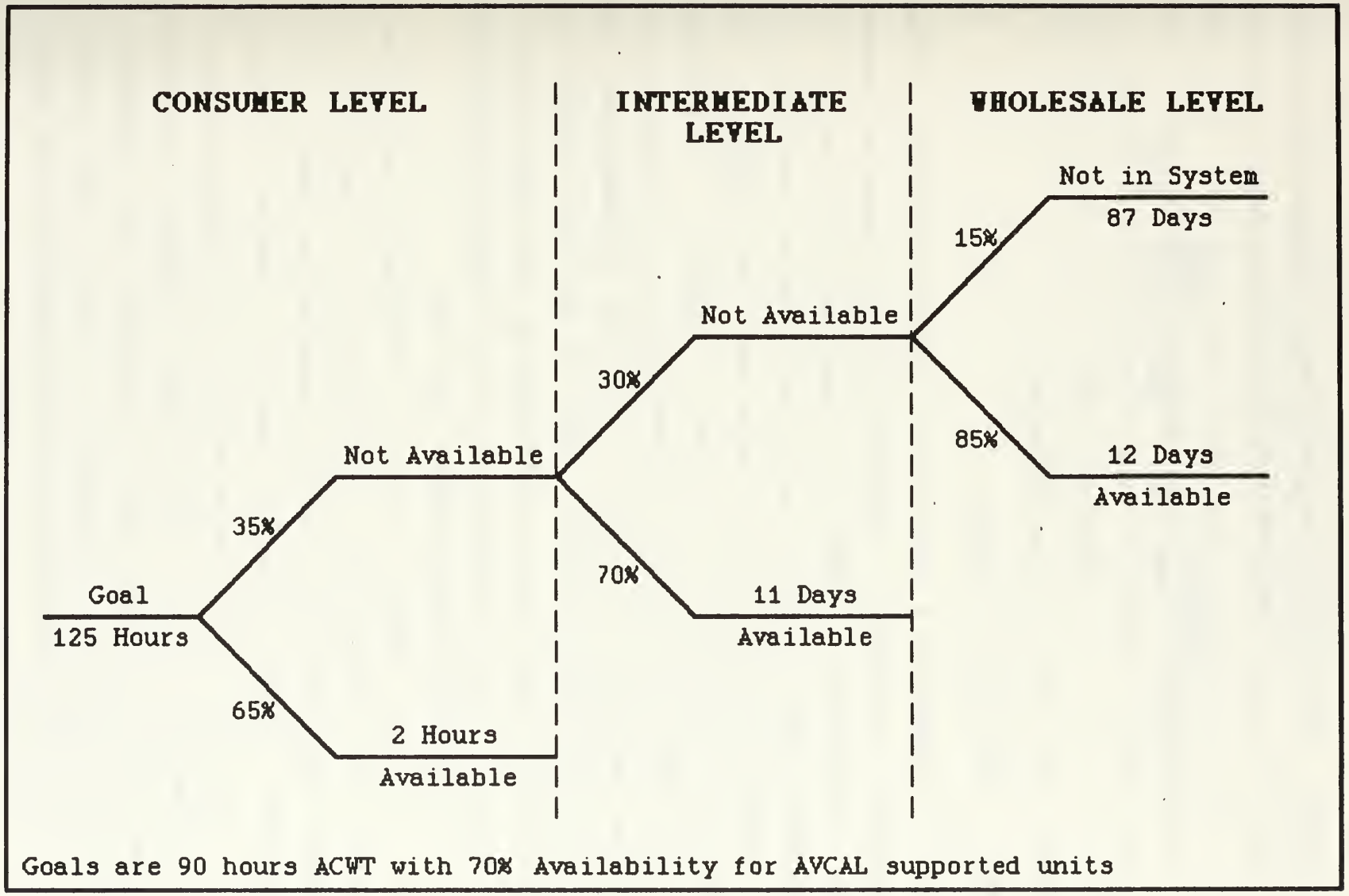

Figure 2.2 CONUS ACWT and Gross Availability Goals (IPG I and II Requirements) [Ref. 12]

environment, will operate satisfactorily when called upon" [Ref.16,p.65]. A_o is expressed mathematically as:

$$A_o = \frac{\text{Up Time}}{\text{Up Time + Down Time}} = \frac{\text{MTBF}}{\text{MTBF + MTTR + MSRT}}$$

where,

MTBF = Mean Time Between Failures;

MTTR = Mean Time to Repair.

MTBF is primarily a function of system reliability which is designed in during the engineering design phase of weapon systems development. MTTR is a function of a variety of maintenance support factors including personnel availability and training, availability of tools and test equipment and system maintainability (i.e., ease of repair). As already indicated, MSRT is a function of availability of repair parts and other materials required to perform preventative and corrective maintenance actions. MSRT is the only variable in the A_o equation which can be controlled by the supply system, and as such, is now considered to be the primary performance measure for the Navy Supply System. [Ref.16]

In the next chapter, the new wholesale repairables inventory model proposed for implementation at the ICP's is presented along with the current repairables model. The mathematical models presently used to compute inventory levels at the Navy's ICP's were adapted from models developed for the commercial sector. These models attempt to minimize the total annual variable costs associated with procuring, stocking and backordering material. As such, they directly relate to the CNO's stated performance objectives for supply response time and operational availability. The new model

proposed for use at the ICP's is fundamentally different from the current models in that it determines the amount of inventory required at the wholesale level to meet a specified MSRT goal. As such, this model would provide the ICP's with the means to directly control MSRT at the wholesale level in consonance with the CNO's and Congress' stated goal of relating resources to combat readiness.

III. THE REPAIRABLES MODELS

The purpose of this chapter is to present the underlying mathematical theory for the new repairables model and discuss the procedure used to compute inventory levels. The current UICP repairables model is also presented for comparison purposes. The opening section describes the Navy repairables cycle and the methodology used to develop the formulas for resupply cycle time and demand during the resupply cycle. This discussion is followed by a detailed presentation of the aggregate demand MSRT model. In the final section, the computational algorithms used in the current UICP integrated repairables model are discussed.

A. MODEL DEVELOPMENT

The first step in developing a mathematical model which reflects the relevant characteristics of a dynamic system such as the repairables inventory system is to identify key events along with their associated times and inter-dependencies. Figure 3.1 graphically depicts the key events in the resupply cycle for the repairables system. Times associated with these events are as follows:

T1 = Carcass turn-in time: the time it takes for a NRFI carcass to be received at the collection point (stock point) after a demand has been registered;

T2 = Carcass waiting time: average time an NRFI carcass waits at the collection point before being sent for repair;

T3 = Shipping time for a carcass from the collection point to the repair activity (DOP);

T4 = Procurement waiting time: average time an inventory deficiency exists due to attrition before an order for replacement units is placed with the manufacturer.

T5 = Shipping time for an RFI unit from the DOP or manufacturer to the stock point;

T6 = Shipping time for an RFI unit from the stock point to the customer;

RTAT = Repair Turnaround Time: time required for the DOP to repair a batch of one or more items and return them to RFI condition;

ALT = Administrative Leadtime: time required by the ICP to prepare purchase documentation and place an order with the manufacturer for replacement items;

PLT = Production Leadtime: time required by the manufacturer to produce the quantity of items purchased;

PCLT = Procurement Lead Time: ALT + PLT + T5;

CTT = Carcass Turnaround Time: T1 + T3 + RTAT + T5.

For this model development, it is assumed that a continuous inventory review policy is followed and current information is always available concerning the status of all material assets in the inventory system. Procurement actions are initiated each time the number of carcass attritions equals the specified order quantity; and NRFI carcasses are sent for repair each time the number of carcasses turned in to the supply system equals the specified repair batch quantity. Additionally, it is assumed that the repair facility has infinite production capacity and will induct and repair all repair batches when received.

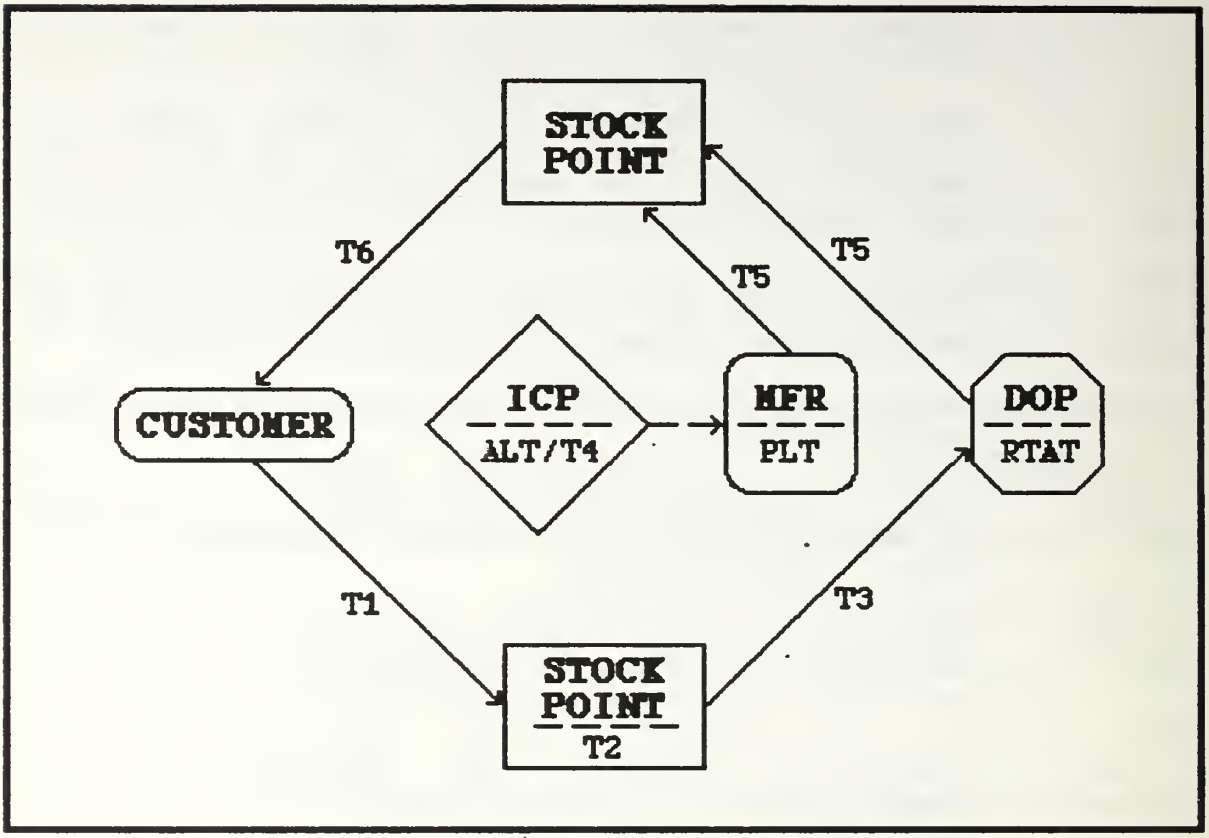

Figure 3.1 Repairables Cycle

As inventory management at the wholesale level is primarily concerned with meeting system-wide demands as opposed to an individual customer's needs, the model used to predict system requirements is built on aggregate forecasts for demand, carcass return rates and repair survival rates. Forecasts for these parameters are generated quarterly at the ICP's using various constrained exponential smoothing models and historical demand data from previous quarters [Ref.7].

In both the UICP integrated repairables model and the MSRT model, the probability that an NRFI item will be returned to the system and survive the repair process is approximated by the product of carcass return rate (CRR) and the repair survival rate (RSR), where,

CRR = Forecasted percentage of NRFI carcasses that will be returned to the wholesale inventory system for repair;

RSR = Forecasted percentage of NRFI carcasses that will survive the repair process.

The CRR and RSR forecasts are multiplied by the quarterly demand rate (D) to obtain a forecast for the quarterly regeneration rate (G):

$$G \cong D*CRR*RSR$$

where,

D = Forecasted quarterly demand rate (or failure rate);

G = Forecasted quarterly regeneration rate: average number of RFI units returned to inventory from the repair process.

The following approximation can now be used to represent the probability that an NRFI item will be returned to the system and survive the repair process:

$$CRR*RSR \cong \frac{G}{D} .$$

Similarly, the probability that an item will be lost through attrition and must be purchased can be represented by:

$$1 - CRR*RSR \cong 1 - \frac{G}{D} .$$

As defined above, the carcass turnaround time (CTT), or time required to process an NRFI carcass through the repair cycle and return it to a stock point in RFI condition, is the sum of T1, T3, RTAT and T5. The total procurement lead time (PCLT), or time required to replace an item lost to the

inventory system through attrition, is the sum of ALT, PLT and T5. In the situation where carcasses are inducted for repair on a one-for-one basis as they are turned in to the system, carcass waiting time at the stock point is negligible and assumed to be zero. Similarly, if a procurement order is placed each time an attrition occurs, procurement waiting time (T4) is also relatively small and assumed to be zero. Using these two assumptions, the total expected resupply cycle time when items are procured and repaired on a one for one basis can be represented by:

$$L^{*} = (1 - CRR*RSR)PCLT + (CRR*RSR)CTT ,$$

or equivalently,

$$L^{*} \cong \left[1 - \frac{G}{D}\right] PCLT + \left[\frac{G}{D}\right] CTT .$$

As shown in the above equations, the repairables system resupply cycle time is a weighted average of the procurement lead time and the carcass turnaround time. The resupply cycle time represents the expected amount of time required to replenish a unit of wholesale system stock which has been requisitioned (demanded) by a customer. Resupply cycle time begins when a demand is recorded against system stock and ends when the issue corresponding to that demand is replaced in the RFI inventory either through repair or procurement action.

When items are procured or repaired in batches as opposed to one for one replacement, waiting times for procurement and repair (T2 and T4) must now be taken into account and the

repairables problem becomes somewhat more complex. Consider the following deterministic examples proposed by Apple [Ref.8] to illustrate the repairables problem first without batching and then with batching.

Figure 3.2 depicts the situation where items are repaired on a one-for-one basis as failures occur. In this example, it is assumed that all NRFI units are returned to the system and repaired at the DOP. The total time required to turn in an NRFI carcass to the inventory system, repair it at the DOP and return it to the stock point in RFI condition is:

$$CTT(R=1) = T1 + T3 + RTAT + T5$$

The total amount of stock required in the wholesale inventory system to preclude the occurrence of a stockout, denoted by SW_R is:

$$SW_R = \left[\frac{CTT(R=1)}{\Delta T}\right]^+$$

where,

ΔT = Time between demands or failures and $[\ ]^+$ denotes rounding up to the next whole integer.

In figure 3.2, ΔT = 0.5 years, RTAT = 0.875 years, T1 = 0.375 years, and T2 = T5 = 0.25 years. CTT is therefore 1.75 years and SW_R is equal to 4.

The situation where NRFI carcasses are allowed to accumulate before repair action is initiated is depicted in figure 3.3. The equation for the total time required to accumulate R units, repair them at the DOP and return them to the stock point in RFI condition now becomes:

$$CTT(R>1) = T1 + T2 + T3 + RTAT + T5$$

where,

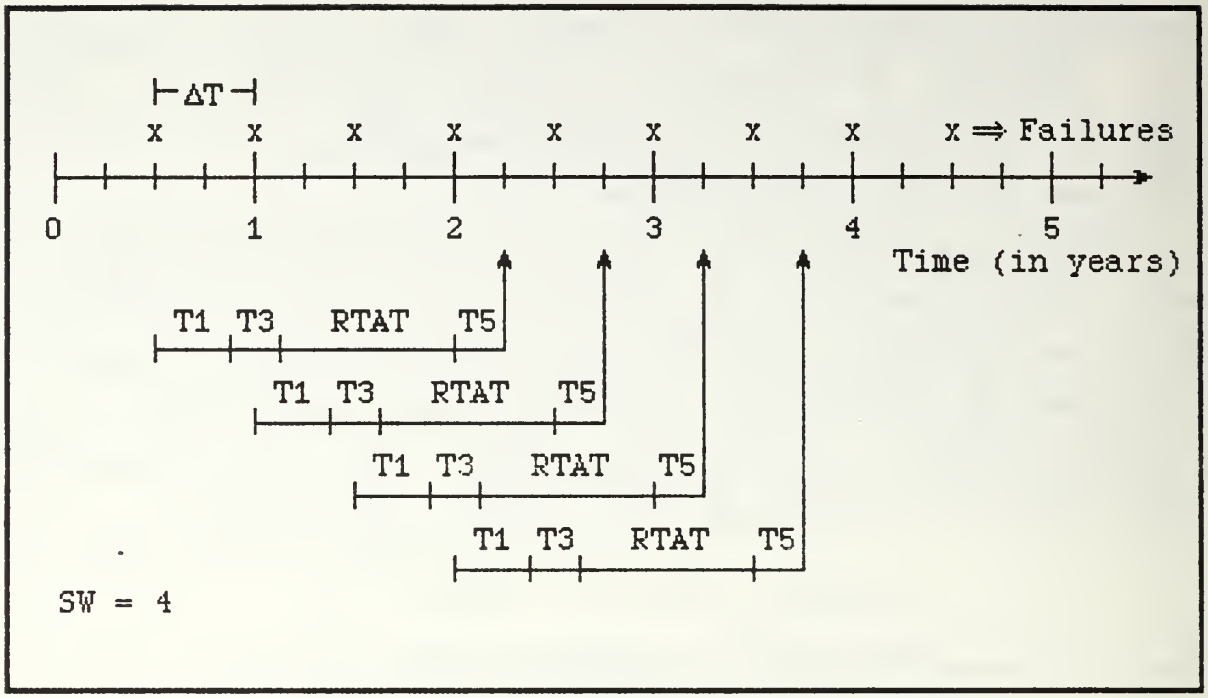

Figure 3.2 Deterministic Model With No Batching.

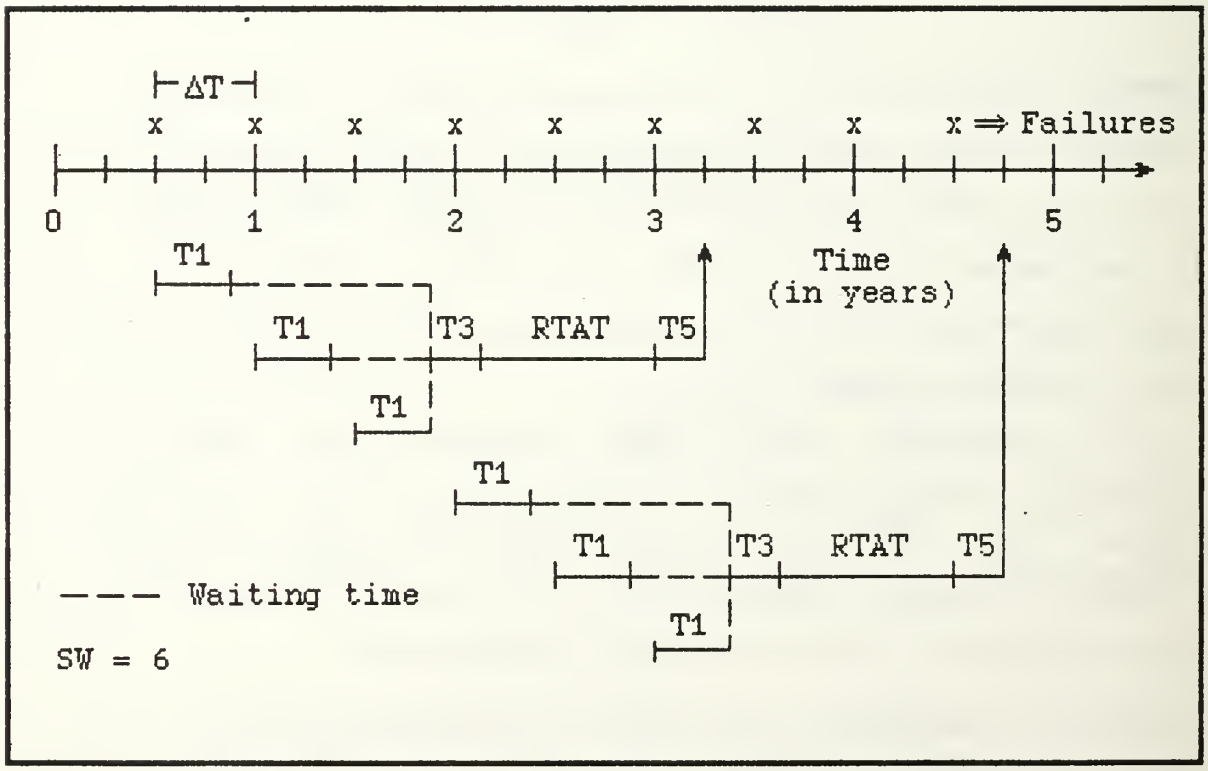

Figure 3.3 Deterministic Model With Batching.

$$T2 = \frac{(R-1)\Delta T}{2} .$$

The total amount of stock required in the inventory system when carcasses are accumulated prior to repair now becomes:

$$SW_R = \left[\frac{CTT(R>1)}{\Delta T}\right]^+ = \left[\frac{CTT(R=1)}{\Delta T} + \frac{R-1}{2}\right]^+ .$$

In Figure 3.3, T1 = .375 years, T3 = T5 = .25 years, ΔT = 0.5 years and RTAT = .875 years as before. However, with R = 3, CTT is now 2.25 years and $SW_R = 6$.

A similar line of reasoning can be followed for the procurement half of the problem where attritions occur at a constant rate until Q units have accumulated and an order is placed with the manufacturer. For this derivation it is assumed that all units are lost through attrition. Here the total procurement cycle time is:

$$PCLT(Q>1) = T4 + ALT + PLT + T5 ;$$

and the amount of system stock required to preclude a stockout is:

$$SW_Q = \left[\frac{PCLT(Q>1)}{\Delta T}\right]^+ = \left[\frac{PCLT(Q=1)}{\Delta T} + \frac{Q-1}{2}\right]^+ .$$

In the actual situation where demands, attritions and all associated times are random variables, the expected increase in resupply cycle time resulting from batch procurements and repairs (W(T)) can be represented by:

$$W(T) = \left[1 - \frac{G}{D}\right] W(Q) + \left[\frac{G}{D}\right] W(R)$$

where,

W(Q) = Average amount of time an attrition waits in the queue at the ICP before procurement action is initiated.

W(R) = Average amount of time an NRFI carcass waits in the queue at the stock point (or DOP) before repair action is initiated.

Under the assumption that times between failures are exponentially distributed, demands at the wholesale level occur according to a Poisson process. Again, looking first at the repair half of the problem, the time between arrivals in the carcass queue can be expressed as:

$$\Delta T = \frac{1}{G} .$$

The number in the repair queue ranges from 0 to R-1 units as shown in the deterministic example and constitutes a continuous Markov chain [Ref.7] The average number of units in the repair queue at a random point in time is:

$$\frac{R-1}{2} ,$$

and the average time an NRFI carcass waits in the repair queue now becomes:

$$W(R) = \frac{R-1}{2G} .$$

For the procurement half of the problem, the average time between arrivals (or attritions) is represented by:

$$\Delta T = \frac{1}{D-G}$$

where,

D-G = The quarterly attrition rate.

The average number of attritions in the procurement queue is:

$$\frac{Q-1}{2},$$

and the average waiting time in the procurement queue is:

$$W(Q) = \frac{Q-1}{2(D-G)}.$$

As determined previously, the expected cycle time or resupply time when units are procured or repaired on a <u>one for one basis</u> is represented by L^*. Accordingly, the total expected resupply time when batching of repairs and procurements is allowed can be expressed as:

$$L = L^* + \left[1 - \frac{G}{D}\right] W(Q) + \left[\frac{G}{D}\right] W(R).$$

By substituting in the full expressions for W(Q) and W(R) and collecting terms, the total expected resupply cycle time becomes:

$$L = L^* + \frac{Q-1}{2D} + \frac{R-1}{2D},$$

and mean demand over this resupply time is:

$$D*L = D\left[L^* + \frac{Q-1}{2D} + \frac{R-1}{2D}\right]$$

$$= DL^* + \frac{Q-1}{2} + \frac{R-1}{2}$$

$$= PPV + \frac{Q-1}{2} + \frac{R-1}{2}$$

where,

PPV = DL^{*} and is called the Procurement Problem Variable in the current ICP integrated repairables model.

This is the formula for mean demand over resupply cycle time for the aggregate demand model presented by Gormly [Ref.9].

B. THE MSRT MODEL

The aggregate demand MSRT model presented by Gormly is a time-weighted units short model which attempts to minimize the total investment level for a particular group of repairable items subject to a specified mean supply response time goal. Alternatively, the Gormly model can be used to compute the aggregate minimum MSRT attainable for a group of items when an investment level constraint is imposed. The first form of the model uses marginal analysis to determine the wholesale stock level for each item by comparing the ratio of reduced response time to the additional investment cost incurred when one more unit of stock is added to the wholesale inventory. Unlike the current ICP model which attempts to determine the optimal procurement and repair reorder points and order quantities for each item independently, this model determines the total amount of wholesale stock required in the system to achieve a specified response time goal using repair and procurement order quantities as input parameters.

The formal statement of the aggregate demand MSRT model is to find the wholesale stock level (SW_i) for each item i, for i = 1,2,3...n, which:

minimizes: $$\sum_{i=1}^{n} C_i SW_i ,$$

subject to: $$\frac{\sum_{i=1}^{n} D_i E_i MSRT_i(SW_i)}{\sum_{i=1}^{n} D_i E_i} \leq \text{MSRT Goal}$$

where,

C_i = Unit procurement cost for item i;

SW_i = Wholesale stock level for item i;

D_i = Quarterly demand rate for item i;

E_i = Essentiality weight for item i;

$MSRT_i(SW_i)$ = Mean supply response time for item i when stocked at a level SW.

The total investment level in this equation is equivalent to the value of the repairables portion of the Navy Stock Fund corpus as discussed in Chapter II. The essentiality weight (E_i) is included as required by DOD Instruction 4140.39, "Procurement Cycles and Safety Levels of Supply for Secondary Items", and is used to determine the relative importance of items with respect to one another [Ref.17]. For a more detailed discussion of the essentiality weight, the reader is referred to Gormly [Ref.9].

In order to find the optimal inventory level for each item which minimizes the total investment in wholesale stock, an equivalent expression for $MSRT_i(SW_i)$ is needed. Apple drew upon Hadley and Whitin's expression for expected time-weighted units short per unit of time to develop an

equivalent expression for $MSRT_i(SW_i)$ [Ref.9]. Unfortunately, while Apple's use of Hadley and Whitin's time-weighted units short concept was theoretically correct, the formula he derived for use in the original MSRT model was subsequently found to be inconsistent with that presented by Hadley and Whitin in *Analysis of Inventory Systems* [Ref.18]. The correct formula for the steady-state time-weighted units short adapted for use in the MSRT model is described in the following paragraphs.

As shown by Hadley and Whitin [Ref.18,pp.181-182], the inventory position for a lot size reorder point model with stochastic demands ranges from the reorder point to the reorder point plus the order quantity. For the proposed repairables model, the order quantity is Q if a procurement is made and R if a repair batch is inducted. The expected order quantity (E(QR)) for a resupply cycle is a weighted average of Q and R, where weighting is a function of the demand rate (D) and the regeneration rate (R) (subscripts are dropped for convenience):

$$E(QR) = \left[1-\frac{G}{D}\right]Q + \left[\frac{G}{D}\right]R .$$

This formula shows that Q units will be ordered for that fraction of the total resupply cycle time corresponding to 1-(G/D), and R units will be ordered for that fraction of the total resupply cycle time corresponding to G/D. These fractions also correspond to the probability that an NRFI carcass will be lost to the system (i.e. not returned by the customer or not repairable) and the probability that an NRFI carcass will be returned and repaired, respectively.

As a procurement is made each time Q attritions accumulate, and a repair batch is inducted each time R NRFI carcasses accumulate, the expected reorder point can be written as:

$$ROP = SW - E(QR).$$

The expected inventory position for the repairables problem then varies between (SW-[E(QR)+1]) and SW. According to Hadley and Whitin [Ref.18,p.182] the associated probability distribution for the inventory position is uniform with each possible value having a probability of:

$$\frac{1}{E(QR)}.$$

Using the assumption that demand during resupply time is described by the Poisson probability distribution with a mean of DL^*, Hadley and Whitin [Ref.18,pp.184-185] showed that the expected number of backorders at a random point in time can be expressed as:

$$B(SW,E(QR);DL^*) = \frac{1}{E(QR)}\left[\beta(ROP) - \beta(SW)\right]$$

where,

$$\beta(x) = \frac{(DL^*)^2}{2}H(x-1) - (DL^*)(x)\left[H(x)\right] + \frac{x(x+1)}{2}H(x-1) \ ;$$

$$H(x) = \sum_{u=x}^{\infty} p(u;DL^*) \ ;$$

$$p(u;DL^*) = \frac{(DL^*)^u e^{-DL^*}}{u!}, \quad u = 0,1,2,3,\ldots\ldots$$

In situations where DL^* is sufficiently large (say > 20.0) the Normal approximation may be used for $\beta(x)$:

$$\beta(x) = \frac{(DL^*)^2}{2}\left\{ \Phi(t)[1+t^2] - t\phi(t) \right\}$$

where,

$\sqrt{DL^*}$ = σ (the standard deviation) is assumed;

$$t = \frac{x-DL^*}{\sqrt{DL^*}} ;$$

$\phi(\cdot)$ is the standardized Normal density function with mean of zero and standard deviation of one;

$\Phi(\cdot)$ is the complementary cumulative distribution function for the standardized Normal distribution;

Hadley and Whitin [Ref.18,p.184] also argued that the expected number of backorders at a random point in time is computationally equivalent to the expected time-weighted units short per unit time (TWUS):

$$TWUS = B(SW, E(QR); DL^*) .$$

The time-weighted units short concept can be illustrated graphically as shown in Figure 3.4. In Figure 3.4, the shaded area at the end of the resupply cycle time (L^*) represents the expected time-weighted units short (i.e., the expected number of unit shortage-quarters in a resupply cycle).

Returning to the equation for $MSRT(SW_i)$; by dividing the expected time-weighted units short by the quarterly demand, Gormly [Ref.9] obtained the average time delay per failure or

mean supply response time (expressed in quarters):

$$MSRT_i(SW_i) = \frac{TWUS_i(SW_i)}{D_i} .$$

To convert to the ICP convention of days, we multiply by 91, the average number of days in a quarter:

$$MSRT_i(SW_i)(days) = \frac{91(TWUS_i(SW_i))}{D_i} .$$

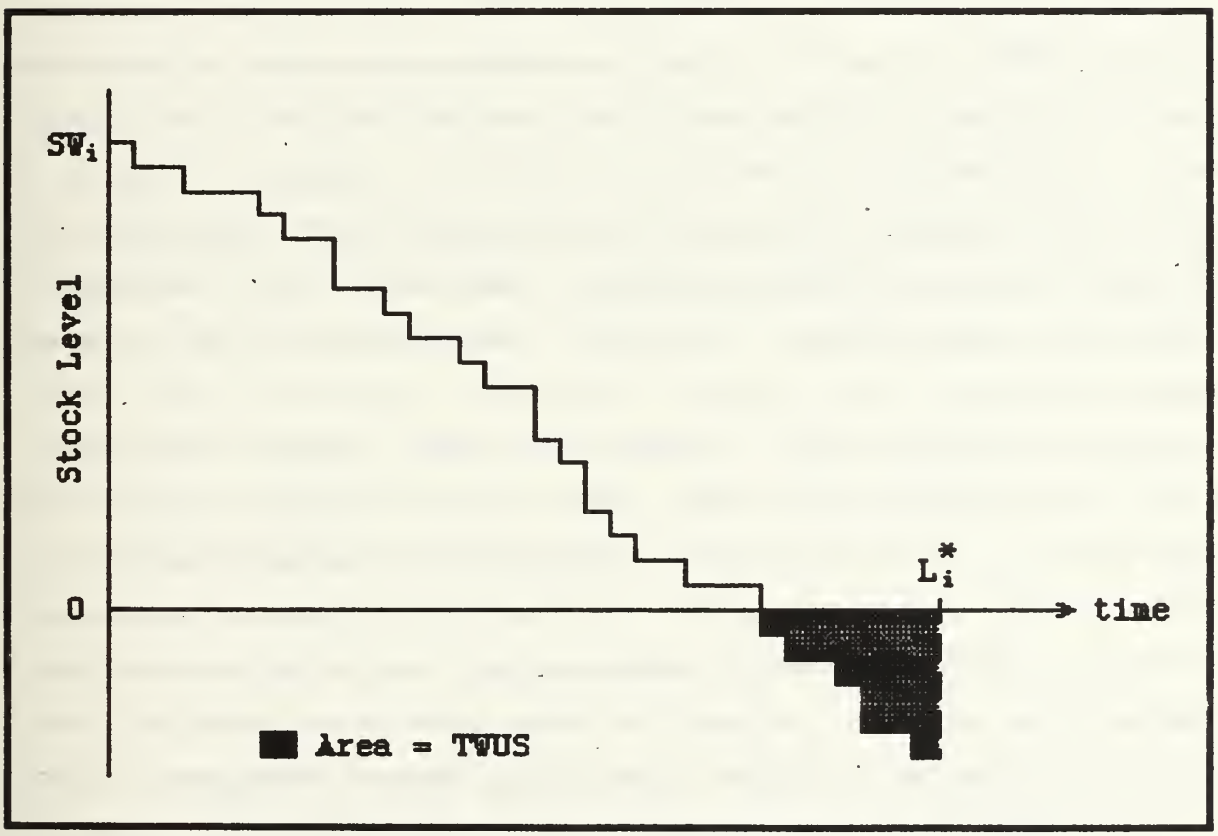

Figure 3.4 The Concept of Time-Weighted Units Short.

The aggregate MSRT value for n items (ignoring essentiality) is given by:

$$MSRT(SW) = \frac{\sum_{i=1}^{n} D_i MSRT_i(SW_i)}{\sum_{i=1}^{n} D_i},$$

or,

$$MSRT(SW) = \frac{91\sum_{i=1}^{n} TWUS_i(SW_i)}{\sum_{i=1}^{n} D_i}.$$

As already shown, the key parameters in this relationship are DL^* (PPV), Q and R. Input parameters required to compute the procurement problem variable are available in the data bases maintained by ASO and SPCC. Repair induction quantities (R) and procurement order quantities (Q) are input parameters to the MSRT computation determined by procurement workload constraints and/or economical lot size considerations.

The procedure used to determine the optimal wholesale stock level (SW_i) for each item in the corpus begins by setting $SW_i = 0$ and computing the expected time-weighted units short ($TWUS_i$) for each item. An initial aggregate MSRT can then be computed directly by summing the calculated time-weighted units short values for each item and dividing that sum by the sum of all items' quarterly demand forecasts. The attained MSRT is then compared to the MSRT goal.

If the computed MSRT exceeds the MSRT goal on the first try, the process ends at that point and no items are selected for stocking. As this is rarely the case in the real world

situation, the marginal analysis process is initiated by incrementing SW_i for all items to one and computing a cost/benefit ratio (WT_i) for each item:

$$WT_i = \frac{C_i}{TWUS(SW_i-1) - TWUS(SW_i)}$$

This ratio relates the increase in investment cost incurred by adding one more unit of stock to the wholesale level to the benefit obtained in reduced response time.

After weights for all items have been computed, the stock depth for the item having the smallest ratio is increased by one. The aggregate MSRT value is then recomputed and compared to the goal. If the goal has not been reached, the weight for the item whose stock level was incremented is recomputed and the process continues until enough units of each item have been added to just satisfy the MSRT goal.

The final step in the procedure is to compute the total investment level for the corpus. This is easily done by summing the product of the unit cost and the computed stock level over all items. Since the optimal stock level for each item has already been determined through the marginal analysis procedure, this value is the minimum amount of investment required to obtain the specified mean supply response time goal.

Because projected system material availability (SMA) is also of interest to the ICP's, this performance measure can also be computed using Hadley and Whitin's equation for the expected number of baokorders per unit time [Ref.18,p.184]:

$$EB(SW,E(QR),DL^{*}) = \frac{D}{E(QR)}\left[\alpha(ROP) - \alpha(SW)\right]$$

where,

$$\alpha(x) = H(x)[DL^{*} - x] + xp(x) \quad \text{for the Poisson distribution;}$$

or,

$$\alpha(x) = \sqrt{DL^{*}}\,[\phi(t) - t\Phi(t)] \quad \text{for the Normal approximation.}$$

The aggregate expected number of backorders per unit time (again ignoring essentiality) is:

$$EBO(SW) = \sum_{i=1}^{n} EB_i(SW_i, E(QR)_i, DL_i^{*}) \ .$$

Since SMA is the expected fraction of demands filled per unit of time, it can now be computed as:

$$SMA = 1 - \frac{EBO(SW)}{\sum_{i=1}^{n} D_i} \ .$$

C. UICP INTEGRATED REPAIRABLES MODEL

The current UICP repairables model is an essentiality-weighted requisitions short model based on the lot size reorder point model of Hadley and Whitin [Ref.18]. The objective function for this model attempts to consider all the expected total annual variable costs associated with ordering, holding and backordering a unit of wholesale stock, that is,

TVC = Ordering Costs + Holding Costs + Backorder Costs.

Ordering costs include internal administrative costs incurred by the ICP to negotiate a procurement contract with the manufacturer and any set-up costs incurred by the

manufacturer to go into production. Holding costs are those costs associated with maintaining on hand inventories. Holding costs include costs of storage, obsolescence, damage or pilferage and opportunity costs. Shortage costs attempt to estimate the cost to the system for incurring backorders. Since the actual shortage cost is impossible to determine, the shortage cost computed in the UICP model is an imputed cost which is used to set inventory levels to meet a specified SMA performance goal.

The goal of the UICP integrated repairables model is to determine the optimal procurement and repair quantities for each item stocked at the wholesale level and their associated reorder points which minimize the total expected annual variable costs. While this can be easily done via standard calculus for a consumables model where there is only one order quantity and one reorder point, the repairables problem is much more complex. Consider the full mathematical expression for the repairables model objective function where the three major terms represent order costs, holding costs and backorder costs respectively:

$$TVC = 4D\left[\left[1-\frac{G}{D}\right]\frac{A}{Q}+\left[\frac{G}{D}\right]\frac{A_2}{Q_2}\right]+I\left[C\left[\frac{Q}{2}\right]+C_2\left[\frac{Q_2}{2}\right]+C^*[SL]\right]+\lambda E[BOR]$$

where G and D and Q and E are defined as before, and

Q_2 = Repair order quantity;

C = Expected item procurement cost;

C_2 = Expected item repair cost;

C^* = Expected cost to the system to repair or replace a unit of stock;

A = Average procurement order/setup cost per order;

A_2 = Average repair order/setup cost per order;

I = Holding cost rate (currently set at $0.21 per dollar of unit value per year for repairables);

SL = Safety level;

λ = Shortage cost parameter used by the ICP's to adjust inventory levels to meet a specified SMA goal

BOR = Expected number of backordered requisitions.

Both the safety level (SL) and the expected number of backordered requisitions are a function of the expected number of units backordered during a resupply cycle. Rather than attempting to derive a mathematical formula for the expected number of backorders in a resupply cycle, the Navy has chosen to borrow selected formulas from the UICP consumables model. In an attempt to satisfy material availability goals and procurement workload constraints, a large number of constraints on repair and procurement quantities and their reorder points.

The actual formulas and computational algorithms used in UICP to compute repair and reorder quantities and reorder points at ASO and SPCC are detailed in the Computation and Research Evaluation System (CARES III) programming algorithms maintained by the Fleet Material Support Office (FMSO)[Ref.19]. These are described below.

The levels determination process for repairables begins with calculation of unconstrained procurement and repair order quantities using two variations of the Wilson Economic Order Quantity (EOQ) formula:

$$Q^* = \sqrt{\frac{8(D-G)A}{IC}}$$ for the Economic Procurement Quantity,

and,

$$Q_2^* = \sqrt{\frac{8\left[\text{MIN}(D,G)\right]A_2}{IC_2}}$$ for the Economic Repair Quantity.

The procurement order quantity is then constrained to ensure that at least one but no more than three years worth of attrition demand are purchased:

$$\tilde{Q} = \text{MIN}\left\{12(D-G), \text{MAX}\left[4(D-G), Q^*\right]\right\}^+$$

And the repair order quantity is constrained to be at least one but no larger than the expected number of repair demands between scheduled repair reviews:

$$\tilde{Q}_2 = \text{MAX}\left[1, (RRCT)(G), Q_2^*\right]^+,$$

where,

RRCT = Repair Review Cycle Time, an ICP set parameter.

UICP calls these two quantities the Basic Order Quantity and Basic Repair Quantity, respectively.

Now the unconstrained stockout risk is computed as:

$$RISK^* = \frac{IC^* D}{IC^* D + \lambda FE}$$

where C^* is defined as before and computed by the following equation:

$$C^* = \left[1-\frac{G}{D}\right]C + \left[\frac{G}{D}\right]C_2$$

and,

F = Requisition frequency (D/Average Requisition Size).

RISK represents the probability that demand during resupply cycle time will exceed the reorder point. Assuming that demand during a resupply cycle follows the Normal distribution, $RISK^*$ can be represented graphically as the area to the right of $DL^* + Z\sigma$ as shown in Figure 3.5.

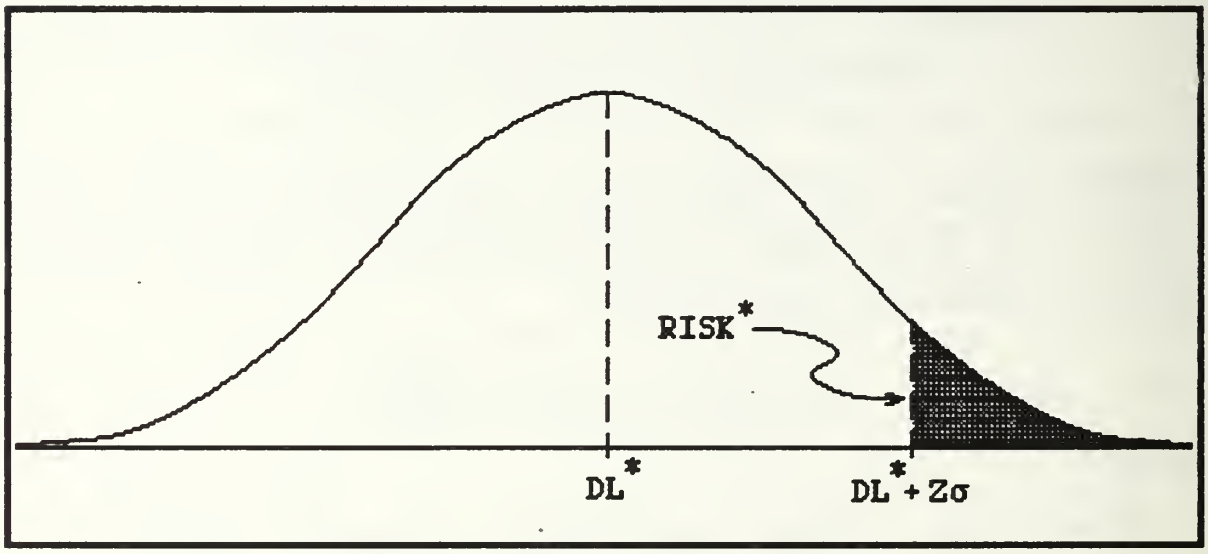

Figure 3.5 Definition of RISK.

In the above figure, DL^* is the mean demand over the resupply cycle (PPV), Z is the standard Normal deviate and σ is standard deviation for demand during resupply time. The safety level (SL) is defined as the product $Z\sigma$.

At both ICP's, $RISK^*$ is constrained to be no less than 0.01 and no larger than a specified value determined separately for different categories of items:

$$\widehat{RISK} = MIN\left[MAX\ RISK, MAX(0.01, RISK^*)\right]$$

The upper bound for RISK is imposed to ensure that the system is not subject to too high a probability of a stockout. The upper bound for all ASO managed items is currently set at

0.5. Upper bounds for SPCC managed items vary from 0.3 to 0.99 for different categories of items classified by a four digit cognizance symbol.

Next the Basic Reorder Level for procurement is computed using either the Normal or Negative Binomial probability distribution. For all items at ASO and most items at SPCC the Normal distribution is used to calculate the procurement reorder point:

$$\tilde{R} = PPV + Z\sqrt{\sigma^2_{DLR}}$$

where,

Z = Number of standard deviations corresponding to the item's acceptable stockout risk (standard Normal deviate);

σ^2_{DLR} = Forcasted demand variance over the resupply cycle.

When the Negative Binomial distribution is used (PPV less than an ICP established break point), SPCC uses a recursion equation to find the smallest R such that:

$$1 - RISK \leq \sum_{x=0}^{R} p(x)$$

where,

p(x) = Probability that demand during resupply time is equal to x, calculated as follows,

$$p(0) = \rho^k$$

and,

$$p(x) = \left[\frac{x+k-1}{x}\right](1-\rho)p(x-1) \qquad \text{for } x = 1,2,3.....R.$$

The parameter ρ is equal to: $\frac{\sigma^2_{DLR}}{PPV}$;

and the parameter k is equal to: $\frac{(PPV)^2}{\sigma^2_{DLR}-PPV}$.

Now the fully constrained repair quantity is determined according to the following algorithm:

$$\hat{Q}_2 = MAX\left[1, MIN\left\{\tilde{Q}_2, \left[4(D)(SHLF) - MAX(0, \tilde{R} - PPV)\right]\right\}^+\right]$$

where,

SHLF = An ICP specified shelf life parameter (not applicable to non-deteriorative items).

The Basic Reorder Level for procurement is next constrained in oonsideration of shelflife restrictions, minimum safety level requirements and the number of policy receivers:

$$\hat{R} = MAX\left[PPV, NSO, MIN\left\{\begin{array}{l}(MSLS/3)(D) + PPV \\ \left[4(D)(SHLF) + PPV\right] - 4(D-G) \\ MAX(\tilde{R} + k, PRS)\end{array}\right\}^+\right]$$

where,

NSO = Numerical stocking objective, an ICP low limit parameter determined independently for each item;

MSLS = Months of safety level stock, an ICP parameter presently set to 99.0);

PRS = Number of policy receivers (i.e. number of wholesale stock points designated to reoeive assets due in from repair or procurement);

k = Repair option, an ICP parameter used to augment the Basic Reorder Level (presently set to 0).

And the Constrained Order Quantity for procurement is constrained to be at least one unit but no larger than the Basic Order Quantity:

$$\hat{Q} = MAX\left[1, MIN\left\{\tilde{Q}, \left[4(D-G)(SHLF) - MAX(0, \hat{R} - PPV)\right]^{+}\right\}\right].$$

Finally, the Basic Repair Level and Constrained Repair Level are determined by adding the procurement safety level to the expected demand during repair turnaround time and making a final check for shelflife restrictions and policy receivers:

$$\tilde{R}_2 = \left[DRTAT + MAX(0, \hat{R} - PPV + k)\right]^{+};$$

$$\hat{R}_2 = MAX\left[0, NSO, MIN\left\{\left[4(D)(SHLF) + (DRTAT - 1)\right], MAX(\tilde{R}_2, PRS)\right\}^{+}\right]$$

where,

DRTAT = Expected demand during repair turnaround time;

k = Repair option as defined previously (k=0).

In the actual repairables levels calculations performed by UICP, four separate repair levels are computed. The four computed levels (levels 1-4) attempt to model the real world situation where repairable assets are severely constrained and repair scheduling is accomplished on a priority basis. Level 1 repairs are for high priority backordered requirements needed to repair a critical system casualty at the consumer level (CASREP, NMCS requisitions); level 2 repairs are for other high priority but less immediate

backordered requirements (established Planned Program Requirements (PPR's) and other end use backorders); level 3 requirements are for stock replenishment backorders, projected PPR's and Pre-positioned War Reserve Stock (PWRS); and level 4 requirements are for stock in anticipation of demand. Levels 2 through 4 are used by CARES to make steady-state performance projections for SMA, ADD and ADDDR. For purposes of comparison between the UICP and MSRT models, only level 4 is used.

IV. MODEL PERFORMANCE COMPARISON

Prior to 1987, performance analyses of the aggregate demand MSRT model were conducted under controlled conditions using small samples of selected inventory management data to evaluate the effects of varying procurement (Q) and repair (R) lot sizes [Refs.9,10]. The logical next step was to perform head-to-head performance comparison tests for the MSRT and UICP models using larger samples of actual inventory management data provided by the ICP's. This chapter summarizes results of performance comparison tests for the MSRT and UICP repairables models conducted during the spring of 1987.

A. MODEL PROGRAMMING

During January and early February 1987, the MSRT model and an approximation of the UICP Integrated Repairables model were programmed in FORTRAN 66 on the IBM 3033 mainframe computer at the Naval Postgraduate School. The program was designed to compute inventory levels for up to 1000 items of stock extracted from 3 CARES work tapes provided by ASO and SPCC. Two of the tapes were provided by SPCC and contained inventory management data for 174,472 consumable and repairable items. Although the data from SPCC dated from 1984, it was considered valid for test purposes. A third tape was provided by ASO and dated from 1986. It included inventory management data for 211,168 items (both consumables and repairables).

Test runs were made using data samples from the 7G, 7H and 7R cognizance categories. 7G and 7H items are non-

aviation depot level repairables (DLR's) managed by SPCC. 7G items are exclusively electronic repairables while 7H items are hull, mechanical and electrical (HM&E) repairables. 7R items are aviation DLR's managed by ASO. The total numbers of items on the tapes for these three categories are as follows:

7G - 12,269
7H - 30,884
7R - 39,258
TOTAL - 82,411

In order to facilitate processing, separate files for each of the three cognizance groups were established on the IBM 3033 mass storage system. Additionally, a fourth file containing input parameters used by the ICP's for computation of levels in the UICP model was also established. Selected data from one of the three DLR files and the input parameter file were read in at the beginning of the program to be used for levels computations.

Thirteen groups of items were selected for analysis from the total item population on the basis of four-digit cognizance symbols. The four-digit cognizance symbol (or COG) is used by the ICP's to segregate items within each major category into smaller management groups of similar items for levels setting. The first two digits of the four-digit COG are the same as the two-digit cognizance symbol (e.g. 7G, 7H). The last two digits indicate the subgroup to which the item is assigned. In UICP, inventory levels are computed separately for each item using different shortage cost parameters (λ's) determined for each four-digit COG group.

Policy for grouping of items for levels computations is fundamentally different at the two ICP's. At SPCC, items are grouped according to three major criteria: item essentiality, frequency of demand and weapons system segmentation. The third digit in the SPCC four-digit COG is the Item Mission Essentiality Code (IMEC). The IMEC is an integer code from 0 to 4 assigned to each item to give some indication of the relative importance of the item in the system. IMEC's are not actually used in the levels computation process as they are only subjective indicators and do not quantify the relative essentiality of items with respect to one another (i.e., an item with an IMEC code of 4 is not necessarily four times as important as an item with an IMEC code of 1, 4 being the highest code assigned).

The fourth digit in the SPCC four-digit COG indicates the demand frequency range and whether the item is weapon system segmented. Codes A and D correspond to a quarterly requisition frequency (RF) of three or more. Codes B and E correspond to a quarterly requisition frequency of less than three but greater than or equal to one. Codes C and F correspond to a quarterly requisition frequency of less than one. Weapon system segmented items are those secondary items identified for support of a single weapon system, while non-weapon system segmented items are common to more than one system. Codes A, B and C are used for non-weapon system segmented items while D, E, and F are used for weapon system segmented items.

At ASO, <u>all</u> secondary items are weapon systems segmented. Additionally, neither requisition frequency or item essentiality are considered in the four-digit cognizance groupings. Instead, ASO uses the item Special Material Identification Code (SMIC) for the last two digits of the

four-digit cog. The SMIC either identifies the item to a specific weapon system (e.g. P-3, A-6, F/A-18 aircraft), or, if the item is used in more than one system, to a group of common equipments (e.g. landing gear, avionics, etc.).

Prior to the computation of levels, each group was screened for items with unusual parameters and life of type buy (LOT) material. All items with zero quarterly demand rates (D), regeneration rates (G), procurement lead time or repair turnaround time variances (σ^2) were eliminated, as were items with excessively high quarterly demands ($\geq$ 250,000). Finally, all items having zero or very small ($5.00 0r less) repair costs were eliminated. All LOT material was also eliminated as cyclical levels are not computed for these items.

Four groups of items from each of the 7G and 7H cognizance categories were selected. Six of the eight groups contained high demand items (RF>3) and the other two contained medium demand items ($1 \leq RF < 3$). Four-digit COG groups having more than 500 items were not selected to keep computer run times to 30 minutes or less. Five groups of items were selected from the 7R cognizance category. These corresponded to major aircraft (EP-3E, A6E, A7, A7E and F/A-18). The larger number of items in some these groups did not cause run time problems as many of the items had very low demand rates or were life of type buy items. The largest group was 7RSF and its run time was still under 30 minutes. The final COGS used in the performance test runs are listed in Table 4.1. The second column lists the total number of items in the group and the third column lists the number of items passing the parameters screen.

TABLE 4.1 TEST RUN SAMPLES

4 DIGIT COG	TOTAL NUMBER OF ITEMS IN COG	NUMBER OF ITEMS PASSING SCREEN
7G0B	114	92
7G1A	165	107
7G2B	176	158
7G4A	75	73
7H1A	145	139
7H2A	147	142
7H3D	255	249
7H4D	131	130
7REP (EP-3E)	674	74
7RGA (A7)	1171	421
7RRA (A6E)	427	266
7RSF (F/A-18)	1538	615
7RTA (A7E)	534	290

After reading in and screening inventory data for unusual parameters, the program computed procurement order quantities and order points for all items using the UICP model. Next, the computed order quantities and order points were added together to obtain the wholesale stock level (SW_i) for each item. The resulting SW_i values were then used to determine expected MSRT values for each item. Finally, the aggregate MSRT, SMA and total investment level for the group were calculated. The process was repeated in the second half of the program running the same items through the MSRT model and using the attained aggregate MSRT from the UICP model as the MSRT goal. In both models, the repair order quantity (R) was set to one. The value of one was chosen for R because both ICP's have a current policy of inducting carcasses for repair on a one-for-one basis as they become available.

Three sets of test runs were made for each group to observe the effects of varying the procurement lot sizes and MSRT goals. In the first set of runs, the procurement

quantity (Q) for the MSRT model was set equal to the UICP computed procurement quantity (Q-UICP). For the second set of runs, Q in the MSRT model was set to one. In the third set of runs, Q for the MSRT model was fixed at Q-UICP and the MSRT goal was varied from 0.01 days to 10.0 days.

B. MODEL PROGRAMMING CHANGES

The first set of performance comparison tests was conducted in February 1987 and the results looked very favorable for the MSRT model. However, in subsequent discussions with operations research personnel at ASO, SPCC and FMSO in late February, a number of questions were raised concerning the validity of performance measures computed for the two models as well as the assumptions used for computation of demand during the resupply cycle for the MSRT model (i.e. MSRT values appeared to be too small and SMA values too large). Performance results for these tests were subsequently invalidated when the formula for time-weighted units short for the MSRT model was found to be inappropriate for the steady-state conditions of replenishment.

Between February and June 1987, the MSRT model was carefully reviewed and reformated as described in Chapter III. Programming for UICP model levels computations was completely revised to conform with the algorithms used in CARES as outlined in Application D, Operation 56 maintained by FMSO [Ref.19]. CARES modules for computation of performance statistics (SMA, ADD and ADDDR) were also added. These will not be presented here, however, because they serve no purpose in the performance comparisons. The revised program code is contained in Appendix A. It should be noted that the CARES subroutines for SMA and ADD were not used for

the second series of comparison tests conducted in June as additional debugging was required.

Performance tests using the reformated programs were conducted in the same manner as the earlier tests. The UICP model was run to compute both the procurement and repair quantities for that model. The procurement reorder points for each item were also computed. Next, the aggregate order quantity for each item was computed using the formula for E(QR) described in Chapter III. The inventory position for each item under the UICP model was assumed to vary from the procurement reorder point (ROP) to ROP+E(QR). The aggregate MSRT was then computed and used as the goal for the MSRT model. The total investment level for each item's maximum inventory position (ROP + E(QR)) was then determined. These values were summed to obtain the total investment level for the group. Aggregate SMA computations were also made using the formula described in Chapter III.

The marginal analysis approach described in Chapter III was used by the MSRT model to compute the optimal maximum inventory position (SW) for each item. The aggregate attained MSRT, total investment levels and SMA were then computed in the same manner as for the UICP model. An item's reorder point for the MSRT model was assumed to be SW-E(QR) for computation of performance measure values.

Two sets of test runs were made for each sample group. In the first set of runs, MSRT model values for Q and R were set equal to the UICP computed procurement and repair quantities. For the second group of runs, Q and R values for the MSRT model were both set equal to one. Results of the test runs are summarized in Tables 4.2 and 4.3 and the end of this chapter.

C. PERFORMANCE TEST RESULTS

In the first set of test runs where UICP computed values for Q and R were used for both models, the MSRT model consistently out-performed the UICP model, both in terms of total investment levels required and attained SMA's. The average reduction in investment level for all sample groups was 5.1 percent. The range of saving was from a low of 1.3 percent for the 7G1A and 7G4A groups, to a high of 12.3 percent for 7RGA group. For 12 of the 13 groups, SMA was marginally higher for the MSRT model. The average increase in SMA for all groups was 1.0 percent.

When procurement and repair quantities for the MSRT model were reduced to one, the savings in investment levels ranged from a low of 6 percent for 7RSF to a high of 35 percent for 7G2B. The average reduction in investment level for all groups was 25 percent. Additionally, SMA values for 11 of the 13 samples were better than those computed for the UICP model.

TABLE 4.2 UICP/MSRT MODELS PERFORMANCE COMPARISON - SPCC MANAGED DLR'S

COG	MSRT GOAL	MODEL	Q	R	INVESTMENT LEVEL	SMA(%)
7G0B	2.598	UICP	UICP	UICP	$ 7,106,195	93.96
		MSRT	UICP	UICP	6,725,271	95.30
		MSRT	1.0	1.0	4,801,002	94.90
7G1A	0.786	UICP	UICP	UICP	$ 15,062,847	97.25
		MSRT	UICP	UICP	14,808,492	97.16
		MSRT	1.0	1.0	10,834,182	96.90
7G2B	2.829	UICP	UICP	UICP	$ 11,456,068	93.56
		MSRT	UICP	UICP	10,739,493	94.33
		MSRT	1.0	1.0	7,385,828	93.78
7G4A	0.357	UICP	UICP	UICP	$ 24,807,370	98.81
		MSRT	UICP	UICP	24,493,345	98.83
		MSRT	1.0	1.0	20,583,766	98.73
7H1A	1.403	UICP	UICP	UICP	$ 46,454,317	96.09
		MSRT	UICP	UICP	44,706,481	97.29
		MSRT	1.0	1.0	34,661,397	97.19
7H2A	1.325	UICP	UICP	UICP	$ 48,037,304	96.61
		MSRT	UICP	UICP	46,184,008	97.69
		MSRT	1.0	1.0	42,328,658	98.29
7H3D	1.628	UICP	UICP	UICP	$ 68,777,140	95.67
		MSRT	UICP	UICP	66,251,671	96.37
		MSRT	1.0	1.0	54,816,636	96.21
7H4D	0.968	UICP	UICP	UICP	$ 23,949,905	96.91
		MSRT	UICP	UICP	23,052,840	97.12
		MSRT	1.0	1.0	17,764,885	96.81

TABLE 4.3 UICP/MSRT MODELS PERFORMANCE COMPARISON - ASO MANAGED DLR'S

COG	MSRT GOAL	MODEL	Q	R	INVESTMENT LEVEL	SMA(%)
7REP	2.716	UICP	UICP	UICP	$ 5,913,225	93.64
		MSRT	UICP	UICP	5,563,864	95.04
		MSRT	1.0	1.0	4,196,008	94.27
7RGA	1.102	UICP	UICP	UICP	$ 63,899,282	96.81
		MSRT	UICP	UICP	56,919,441	97.64
		MSRT	1.0	1.0	42,746,700	97.39
7RRA	1.240	UICP	UICP	UICP	$ 75,408,510	95.67
		MSRT	UICP	UICP	71,710,018	97.08
		MSRT	1.0	1.0	56,797,450	96.96
7RSF	1.459	UICP	UICP	UICP	$309,328,122	96.38
		MSRT	UICP	UICP	291,044,850	99.43
		MSRT	1.0	1.0	290,456,484	96,94
7RTA	0.793	UICP	UICP	UICP	$140,182,434	97.51
		MSRT	UICP	UICP	133,699,129	98.08
		MSRT	1.0	1.0	105,205,010	98.01

V. REPAIRABLES MODEL SIMULATIONS

This chapter summarizes supplemental research conducted during the spring of 1987 for the aggregate demand MSRT model. In order to gain a better understanding of the actual repairables process and verify some of the underlying assumptions for the MSRT model, a single item simulation was programmed in April 1987. The goals for programming the simulation were to: (1) determine where in the repairables cycle backorders were most likely to occur; (2) isolate and identify the probability distribution(s) for demand during resupply time resulting from a stream of Poisson demands; (3) conduct sensitivity analysis to examine the effects of batch procurements and repairs on MSRT and SMA; and (4) identify any discernable recurring patterns in the repairables cycle.

A. SIMULATION PROGRAMMING

The single item repairables simulation was programmed in FORTRAN 77 on the IBM 3033 mainframe computer at the Naval Postgraduate School. The program was designed to simulate all events in the life of a repairable item under steady state conditions under the following assumptions:

1. Demands were generated randomly according to the Poisson distribution;
2. Attritions were generated randomly using a Bernoulli distribution;
3. Procurement leadtimes and repair turnaround times were held constant at their forecasted mean values;
4. Procurement action was initiated each time the number of attritions occurring since the last order equalled the established order quantity (Q);

5. Repair inductions were made each time the total number of NRFI carcasses on hand equalled the established repair batch quantity (R);

6. All units in each repair batch were inducted, repaired and returned to RFI status as a group;

7. More than one repair or procurement order could be outstanding at the same time;

8. The depot repair facility had infinite repair capacity.

The MSRT model simulation was designed to record all individual events occurring in the resupply cycle for a maximum of thirty years. Input parameters were wholesale stock level (SW), demand rate (D), regeneration rate (G), procurement leadtime (PCLT), repair turnaround time (RTAT) and repair survival rate (RSR). Their values were set at the beginning of the program and held constant for the entire simulation. Random demands and attritions were generated using the LLRANDOMII Random Number Generator contained in the non-IMSL subroutine library of the IBM 3033. Performance statistics were generated at the end of each run for SMA, MSRT (ADD) and average days delay for delayed requisitions (ADDDR). Statistics were also computed for average demand (D), regeneration rate (G), carcass return rate (CRR) and repair survival rate (RSR) to provide a check on values generated by the random number subroutine.

Options for both long and short reports were included. The long report included inventory position, on-hand RFI inventory, number of items in the repair and procurement queues, number of items in repair and on order and the number of backorders for each discrete event in the resupply cycle. A second long report option was also included to generate data for plotting of net inventory and inventory position using the DISSPLA graphics application. The short report

option included only summary performance statistics and was used when making comparative runs in which the parameters for Q and R were varied.

At the beginning of each run, on-hand inventory was set equal to SW with no units in the pipelines for either repair or procurement. As NRFI carcasses and attritions accumulated, queues were established for both repair and procurement. Procurement action was initiated each time Q attritions occurred and repair inductions occurred each time R carcasses accumulated. Variable definitions for the simulation program are listed in Appendix B and the full program code is contained in Appendix C.

B. OCCURRENCE OF BACKORDERS

The first objective for programming the simulation was to generate sufficiently large samples of inventory data to determine where stockouts were occurring in the repairables cycle. As the number of individual events occurring over a thirty-year simulation is extremely large (as much as 2400 for an item with a quarterly demand of 10) it was not practical to include the full printouts from the events files in this thesis. Selected excerpts from the full events files are included in this chapter for illustration purposes.

Prior to running the first simulations, it was conjectured that stockouts were most likely to occur near the end of a procurement cycle. While this conjecture was not proved invalid by the simulations, it did prove to be an over simplification of the actual situation which resulted. In virtually all of the simulation test runs, the occurrence of stockouts was more the result of a complex combination of factors with the key determinant being the number of items in

the procurement pipeline at random points in time. This phenomenon is easiest to explain through the use of two examples taken from one of the test runs. Figures 5.1 and 5.2 are excerpts from a thirty-year event profile for an item having the following characteristics:

D	=	8.0 units/qtr.
G	=	7.6 units/qtr. (15% attrition rate)
Q	=	5 = 1 year's attrition demand(4(D-G))
R	=	1
PCLT	=	10.2 qtrs (928 days)
RTAT	=	1.2 qtrs. (109 days)
SW	=	30 units

These parameters resulted in an SMA of approximately 90 percent, an MSRT of 2.4 days and an ADDDR of 22.4 days.

Figure 5.1 shows the inventory system status over a 136 day period overlapping years three and four. The times shown correspond to the last third of the procurement cycle for the first order, the middle of the procurement cycle for the second order and a third order is pending. The two outstanding orders of five units each are due in on days 1780 and 2207 (end of year four and beginning of year six respectively). Additionally, four attritions have already occurred since the last order was placed on day 1278 (deficit column). A third order will be placed on day 1542 when the fifth attrition occurs. Backorders begin occurring intermittently on day 1405, shortly after the third and fourth attritions are recorded, and continue through day 1461. In this example, the relatively large number of units in repair (17-18) in combination with the two outstanding procurement orders contributes to the occurrence of stockouts. Note that in this example the backorders are of

relatively short duration (1 to 8 days) as requisitions are filled promptly from material returning from repair.

Figure 5.2 shows a somewhat different situation in the middle of year nine. In this example we are at the end of the procurement cycle for the oldest order, the middle of the procurement cycle for two orders and the beginning of the cycle for a fourth order. The oldest outstanding order is received on day 3518. The other two orders are due in on days 3779 and 4101 (middle of year 10 and beginning of year 11 respectively). The fourth order is placed on day 3455 when the fifth attrition occurs. Backorders begin occurring steadily as soon as the fourth order is placed and terminate promptly when the oldest order arrives on day 3518. During this same time frame, the number of units in the repair cycle has also increased substantially from four units on day 3375 to a high of sixteen units on day 3480. Here again, the combination of outstanding procurement orders and the increase in the number of units in repair each contribute to the stockout situation. Note that the average number of outstanding backorders in this instance is significantly larger (4-5 units), and the average days delay for filling requisitions is approximately 21 days.

These two examples are fairly typical of the inventory patterns observed in all of the simulation runs for items having a quarterly demand of 5 or more units. Unless the demand rate was set fairly low ($D < 2$/qtr.), there were almost always at least two procurement orders outstanding by the end of the third year and the repair pipeline was never empty. When 50 to 60 percent of SW was in the procurement pipeline, stockouts occurred intermittently until the oldest outstanding order was received. In instances when the number

CLOCK(DAYS)	INV POS	O/H RFI	O/H NRFI	DEFICIT	IN REPAIR	ON ORDER	BACKORDERS
1386.21	26	3	0	4	13	10	0
1388.22	26	2	0	4	14	10	0
1394.14	26	3	0	4	13	10	0
1401.18	26	2	0	4	14	10	0
1403.43	26	1	0	4	15	10	0
1403.64	26	0	0	4	16	10	0
1405.67	26	0	0	4	17	10	1
1413.41	26	0	0	4	18	10	2
1418.19	26	0	0	4	17	10	1
1418.44	26	0	0	4	16	10	0
1435.84	26	1	0	4	15	10	0
1436.55	26	0	0	4	16	10	0
1439.29	26	0	0	4	17	10	1
1446.01	26	0	0	4	16	10	0
1446.68	26	0	0	4	17	10	1
1448.02	26	0	0	4	16	10	0
1453.01	26	0	0	4	17	10	1
1454.73	26	0	0	4	18	10	2
1456.83	26	0	0	4	17	10	1
1457.55	26	0	0	4	16	10	0
1459.86	26	0	0	4	17	10	1
1460.05	26	0	0	4	18	10	2
1461.61	26	0	0	4	17	10	1
1461.92	26	0	0	4	16	10	0
1469.00	26	1	0	4	15	10	0
1474.29	26	2	0	4	14	10	0
1482.62	26	1	0	4	15	10	0
1484.35	26	2	0	4	14	10	0
1489.36	26	1	0	4	15	10	0
1497.42	26	2	0	4	14	10	0
1510.38	26	3	0	4	13	10	0
1512.63	26	4	0	4	12	10	0
1512.84	26	5	0	4	11	10	0
1514.87	26	6	0	4	10	10	0
1522.60	26	7	0	4	9	10	0

Figure 5.1 Simulation Events File Excerpt No.1

CLOCK(DAYS)	INV POS	O/H RFI	O/H NRFI	DEFICIT	IN REPAIR	ON ORDER	BACKORDERS
3375.15	27	8	0	3	4	15	0
3376.34	27	7	0	3	5	15	0
3379.54	26	6	0	4	5	15	0
3383.63	26	5	0	4	6	15	0
3384.87	26	4	0	4	7	15	0
3385.65	26	3	0	4	8	15	0
3395.63	26	2	0	4	9	15	0
3401.59	26	1	0	4	10	15	0
3405.22	26	0	0	4	11	15	0
3410.76	26	0	0	4	12	15	1
3416.22	26	0	0	4	11	15	0
3421.16	26	1	0	4	10	15	0
3438.04	26	2	0	4	9	15	0
3445.03	26	1	0	4	10	15	0
3455.67	30	0	0	0	10	20	0
3457.79	30	0	0	0	11	20	1
3459.45	30	0	0	0	12	20	2
3459.74	30	0	0	0	13	20	3
3471.54	30	0	0	0	14	20	4
3473.15	30	0	0	0	15	20	5
3480.13	30	0	0	0	16	20	6
3484.35	30	0	0	0	15	20	5
3485.54	30	0	0	0	14	20	4
3486.33	30	0	0	0	15	20	5
3492.78	30	0	0	0	16	20	6
3492.83	30	0	0	0	15	20	5
3494.07	30	0	0	0	14	20	4
3494.85	30	0	0	0	13	20	3
3504.83	30	0	0	0	12	20	2
3510.79	30	0	0	0	11	20	1
3514.42	30	0	0	0	10	20	0
3514.96	30	0	0	0	11	20	1
3518.77	30	4	0	0	11	15	0
3519.96	30	5	0	0	10	15	0
3520.14	30	4	0	0	11	15	0

Figure 5.2 Simulation Events File Excerpt No.2

of units in the procurement cycle exceeded 70 percent of SW, stockouts occurred continuously until this percentage dropped back down to just over 50 percent. The average amount of time a backorder was outstanding also increased significantly during these periods. Conversely, stockouts were rarely observed when less than 50 percent of the wholesale stock was in the procurement pipeline. It should be noted that these percentages would increase or decrease depending on the value of SW.

C. DEMAND DURING THE RESUPPLY CYCLE

In both the UICP and MSRT models presented in Chapter III, a key assumption is that the demands occurring during the resupply cycle can be described by a single probability distribution. The distribution for demand during the resupply cycle in the repairables case can not be derived easily because it is a function of the quarterly demand, procurement lead time, repair regeneration rate and the repair turnaround time. While past use of the Poisson assumption provides a convenient method for computing a mathematical solution for the distribution of demand during the resupply cycle, this theory has never been validated for the repairables case. Here the repairables simulation proved to be extremely useful for isolating the distributions resulting from a single stream of Poisson demands.

Prior to generating the first resupply cycle time demand samples, it was conjectured that the resulting distribution would be Poisson with a mean which was the demand during the resupply cycle if the procurement lead time and repair turnaround time were assumed to be constant. However, the situation where queues were allowed to form for the repair

and procurement pipelines complicated the problem and it was not known if the Poisson assumption would be valid for this case.

In order to collect samples for demands occurring during each resupply cycle, an additional subroutine was added to the original simulation program in May 1987. This routine computed the total number of demands occurring between the time a demand was received by the system and the time the corresponding issue was replaced in inventory either through procurement or repair action. Thirty-year inventory simulations were used to generate sufficiently large samples for statistical analysis. Raw demand data generated by the simulation program was transferred to an Apple Macintosh PC file to compute statistics, perform goodness of fit tests and generate histograms for demand during the resupply cycle. The Statworks application program was used for statistical analysis and to generate histograms. Two separate FORTRAN 77 routines were written to perform Chi squared (χ^2) goodness of fit tests for the Poisson distribution. The first routine used a Poisson recursion equation to perform the χ^2 goodness of fit test. The second program used a Normal approximation to perform the fit test.

A total of twelve separate simulations were run for analysis. Input parameters for D, PCLT, RTAT, and SW were held constant at the following values for all samples:

D = 10.0 units/qtr
PCLT = 10.2 qtrs (928 days)
RTAT = 1.2 qtrs. (109 days)
SW = 35 units

Six of the runs were made with Q=4 and R=5. The other six runs were made with Q=1 and R=1. The first two runs for each group were made using a 10 percent attrition rate (i.e., G/D = 0.90). In subsequent runs, attrition rates of 50, 70 and 90 percent were used. This was done both to observe the effects of routing more units through the procurement cycle and to generate sufficient numbers of observations to perform reliable goodness of fit tests. Each simulation run generated between 1100 and 1200 observations which was more than sufficient in the majority of cases to perform χ^2 goodness of fit tests at the 95 percent confidence level.

Figure 5.3 shows the histogram for the first simulation with Q=4, R=5 and a 10 percent attrition rate. Like all the simulation runs using PCLT=10.2 quarters and RTAT=1.2 quarters, two distinct demand distributions resulted. The tall distribution on the left corresponds to demands that occurred during repair turnaround times (DRTAT). The flat distribution on the right corresponds to demands that occurred during procurement lead times (DPCLT).

Because the actual distribution for during the resupply cycle could not be obtained directly from the simulation, each of the two distinct distributions were checked separately for a fit to the Poisson distribution. If both were found to fit, then the distribution of demand during the resupply cycle is also Poisson since it is a convex combination of the two separate distributions.

Equations used to compute the means for the null hypothesis are as follows:

$$\mu(\text{DRTAT}) = (D)(\text{RTAT}) + \frac{R-1}{2},$$

and,

$$\mu(DPCLT) = (D)(PCLT) + \frac{Q-1}{2} .$$

For all observations associated with Q=4/R=5, the computed means for the null hypotheses were 14.0 and 103.5 for DRTAT and DPCLT respectively. When Q=1/R=1 was used, the computed means for the DRTAT and DPCLT null hypotheses were 12.0 and 102.0, respectively.

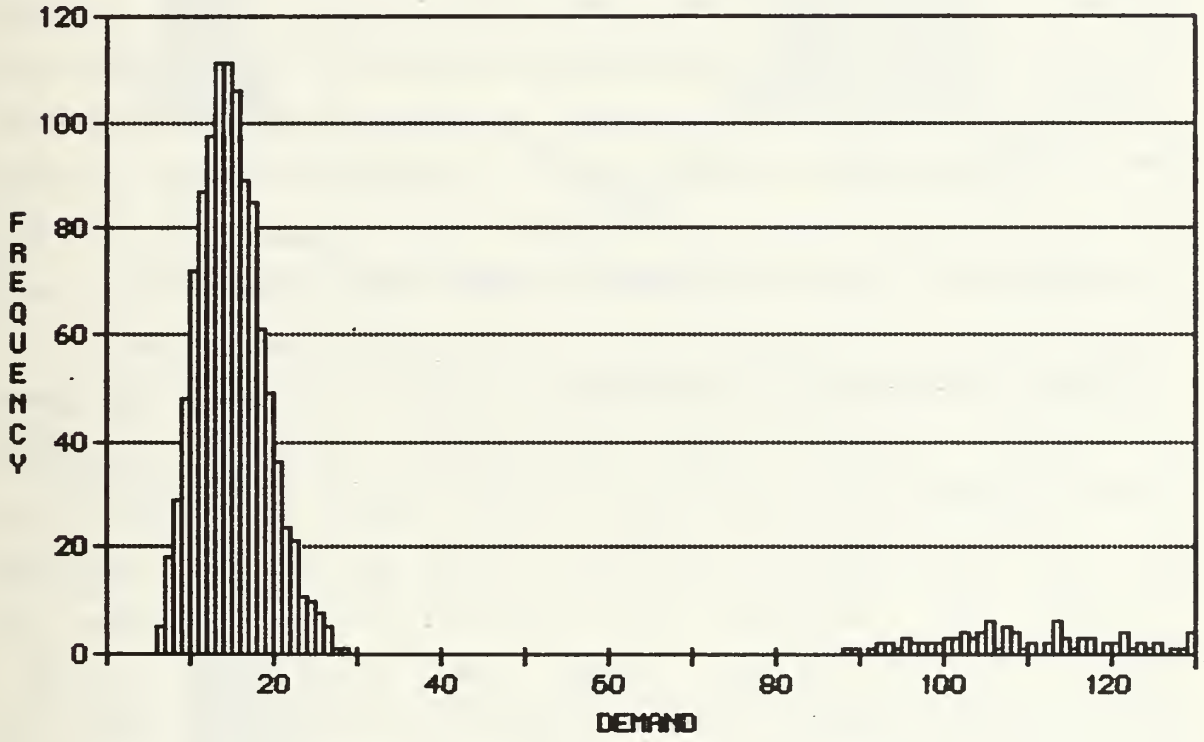

Figure 5.3 Demand During Resupply Histogram No.1

For each of the four simulations in which the attrition rate was set at 10 percent, the DRTAT half of the histogram consistently matched the Poisson probability distribution at the 95 percent confidence interval regardless of whether R=1 or R=4. The DPCLT half of the histogram for the 10 percent

attrition runs had too few observations to obtain any reliable results. As the attrition rate was increased from 70 to 90 percent in subsequent runs, the sample sizes for DPCLT eventually became large enough to compute reliable statistics. However, of the four DPCLT simulations using a 90 percent attrition rate, only one provided a fit to the Poisson distribution at the 95 percent confidence interval. The other three simulations did not even provide good fits at the 50 percent confidence interval.

Figures 5.4 and 5.5 show the resulting demand during resupply cycle histograms generated using a 50 percent attrition rate. The histogram in Figure 5.4 was generated using Q=1/R=1 and the histogram in Figure 5.5 used Q=4/R=5. These two histograms are included to provide a better picture of the demand during procurement lead time half of the distribution. The horizontal scale for demand in both histograms uses the same scale to facilitate comparison.

There are several observations worthy of comment in these two figures. First of all, the medians for DRTAT and DPCLT in both figures are very close to the theoretical means (12.0 and 102.0 for Q=1/R=1 and 14.0 and 103.5) for Q=4/R=5) Secondly, the variances for the Q=4/R=5 distributions in Figure 5.5 are visibly larger than those for Q=1/R=1. Thirdly, when comparing the variances for DRTAT and DPCLT in each of the respective figures, the variance for DRTAT is noticeably smaller in each case. This observation is consistant with the theoretical Poisson variance which is equal to the square root of the mean. Although less obvious, the DPCLT plots have a significantly higher number of demands centered around the mean than is normal for a Poisson distribution with a mean close to 100. This could be seen more clearly when comparing the theoretical expected values

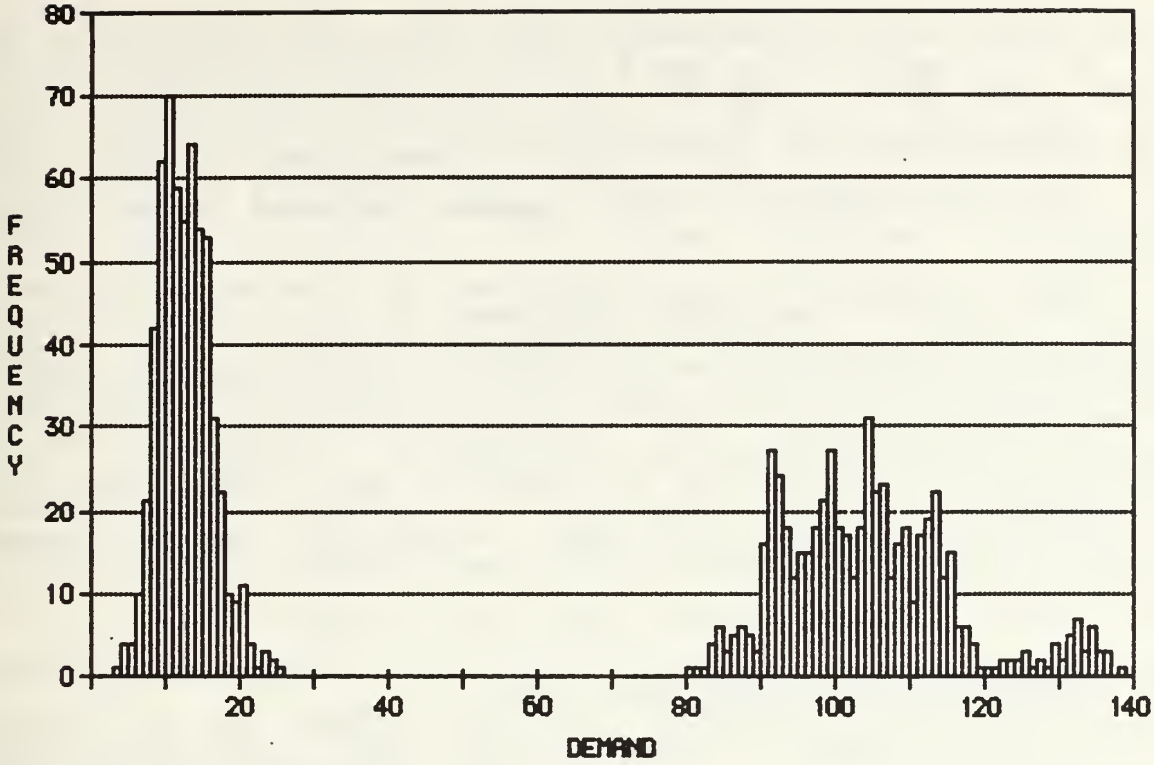

Figure 5.4 Demand During Resupply Histogram No.2 (Q=1/R=1)

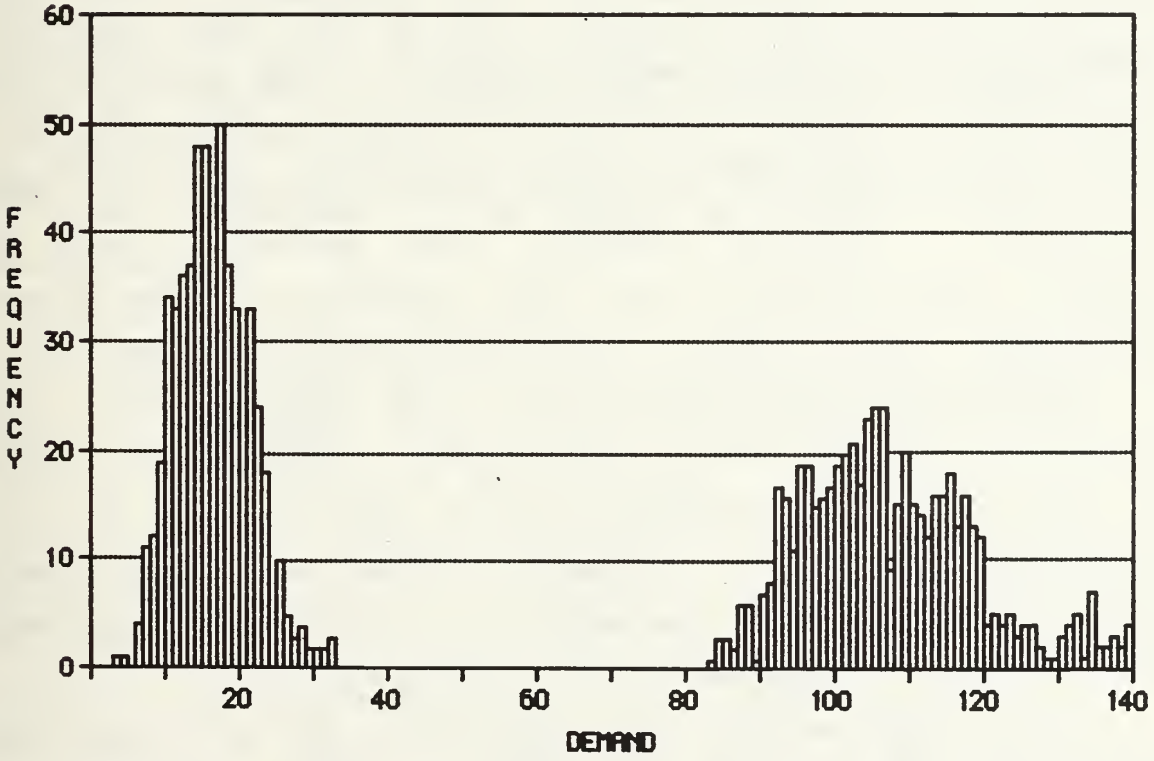

Figure 5.5 Demand During Resupply Histogram No.3 (Q=4/R=5)

for DPCLT with the observed values when the goodness of fit tests were made. Finally, the right tail for DPCLT in 10 of 12 simmulations was significantly longer than the left tail. In only one histogram were demands recorded below 80 for DPCLT.

As results for DPCLT goodness of fit tests did not satisfy the hypothesis of a Poisson distribution for most of the simulation runs, the distribution of demand during the resupply cycle could not be shown to be Poisson, even when procurement lead time and repair turnaround time are assumed to be constant.

D. SENSITIVITY ANALYSIS FOR Q AND R

As discussed in Chapter III, when procurements and repairs are batched, the wholesale stock level must be increased to compensate for the additional time NRFI carcasses and attritions spend waiting in their respective queues prior to orders being initiated. The focus of this effort was to observe the effects various combinations of Q and R had on SMA, MSRT and ADDDR using the single item model simulation. For this analysis, input parameters were the same as those used in the first example of this chapter except that the values for Q and R were varied for each run..

Three simulations were run for each combination of Q and R using different random number seeds. Although the number of runs for each combination of Q and R values was not sufficient to compute reliable statistics, results were relatively consistent between runs and were considered satisfactory for this sensitivity analysis.

Performance results from one full set of simulations using the same random number seed are summarized in Tables

5.1 and 5.2. For the first group shown in Table 5.1, Q values were held constant while R was varied from 1 to 8. In the second group shown in Table 5.2, R values have been held constant and Q varied from 1 to 8. Performance results for MSRT were consistent with those obtained using the theoretical model. In each case, as the number of units in either the repair or procurement batches increased, model performance decreased for all three statistics, although not at the same rates. As expected, setting Q and R equal to one consistently resulted in the best overall performance. Finally, it is interesting to note that regardless of whether Q or R was varied while the other remained fixed, the performance results were very similar. This may be the result of the combination input parameters used and should not be generalized for all cases.

As discussed by Pearsall [Ref.10], the size of the procurement order quantity is a variable of primary concern for the ICP's as Q has a direct effect on procurement workload. While the optimal order policy for the MSRT model is one-for-one replenishment, this policy is impractical if an item experiences a large number of demands or has a high attrition rate.

Referring again to Table 5.2 where Q was incremented, MSRT and SMA values for Q>1 are not significantly larger than for Q=1, providing R is relatively small (2 to 3 units). However, as Q and/or R become larger, MSRT increases at an increasing rate. This observation is illustrated graphically in Figures 5.6 and 5.7. Figure 5.6 depicts the MSRT plots for the five runs in which R was held constant and Q varied. Data for this plot was taken directly from Table 5.2.

Figure 5.7 shows a comparative plot of MSRT versus SMA for R=1 and Q varied from 1 to 8. Note here that SMA

TABLE 5.1 PERFORMANCE STATISTICS FOR Q CONSTANT/R VARIED

Q	R	MSRT(days)	ADDDR(days)	SMA(%)
1	1	0.960	18.928	94.93
1	2	1.101	18.405	94.02
1	3	1.544	20.297	92.39
1	4	1.855	20.780	91.08
1	5	2.427	22.159	89.05
1	6	2.970	23.431	87.32
1	7	4.089	26.348	84.48
1	8	4.747	27.371	82.66
2	1	1.223	18.845	93.51
2	2	1.440	19.182	92.49
2	3	2.017	20.504	90.16
2	4	2.391	21.633	88.95
2	5	3.073	23.857	87.12
2	6	3.717	24.111	84.58
2	7	5.062	28.358	82.15
2	8	5.720	28.483	79.92
3	1	1.532	18.195	91.58
3	2	1.852	18.266	89.86
3	3	2.609	20.917	87.53
3	4	3.123	22.313	86.00
3	5	3.890	24.589	84.18
3	6	4.607	25.238	81.74
3	7	6.349	29.670	78.60
3	8	7.108	30.339	76.57
4	1	1.859	19.713	90.57
4	2	2.216	20.805	89.35
4	3	3.011	22.840	86.82
4	4	3.514	23.896	85.29
4	5	4.342	24.892	82.56
4	6	5.396	25.701	79.01
4	7	7.077	30.076	76.47
4	8	7.989	30.651	73.94
5	1	2.412	22.439	89.25
5	2	2.837	23.312	87.83
5	3	3.663	23.916	84.69
5	4	4.413	24.306	81.85
5	5	5.507	27.286	79.82
5	6	6.541	25.492	74.34
5	7	8.917	30.742	70.99
5	8	9.731	31.152	68.76

TABLE 5.2 PERFORMANCE STATISTICS FOR R CONSTANT/Q VARIED

Q	R	MSRT(days)	ADDDR(days)	SMA(%)
1	1	0.960	18.928	94.93
2	1	1.223	18.845	93.51
3	1	1.532	18.195	91.58
4	1	1.859	19.713	90.57
5	1	2.412	22.439	89.25
6	1	3.573	24.133	85.19
7	1	4.452	26.842	83.89
8	1	5.806	29.209	80.12
1	2	1.101	18.405	94.02
2	2	1.440	19.182	92.49
3	2	1.852	18.266	89.86
4	2	2.216	20.805	89.35
5	2	2.837	23.312	86.83
6	2	4.162	26.140	84.08
7	2	5.073	27.484	82.66
8	2	6.786	29.608	77.08
1	3	1.544	20.297	92.39
2	3	2.017	20.504	90.16
3	3	2.609	20.917	87.53
4	3	3.011	22.840	86.82
5	3	3.663	23.916	84.69
6	3	5.338	29.079	81.64
7	3	6.358	29.549	77.82
8	3	8.361	31.828	73.73
1	4	1.855	20.780	91.08
2	4	2.391	21.633	88.95
3	4	3.123	22.313	86.00
4	4	3.514	23.896	85.29
5	4	4.413	24.306	81.85
6	4	6.053	28.833	79.01
7	4	7.255	29.358	75.27
8	4	9.639	32.999	70.79
1	5	2.427	22.159	89.05
2	5	3.073	23.857	87.12
3	5	3.890	24.589	84.18
4	5	4.342	24.892	82.56
5	5	5.507	27.286	79.82
6	5	7.156	30.283	76.37
7	5	8.676	31.565	73.04
8	5	11.267	35.954	68.66

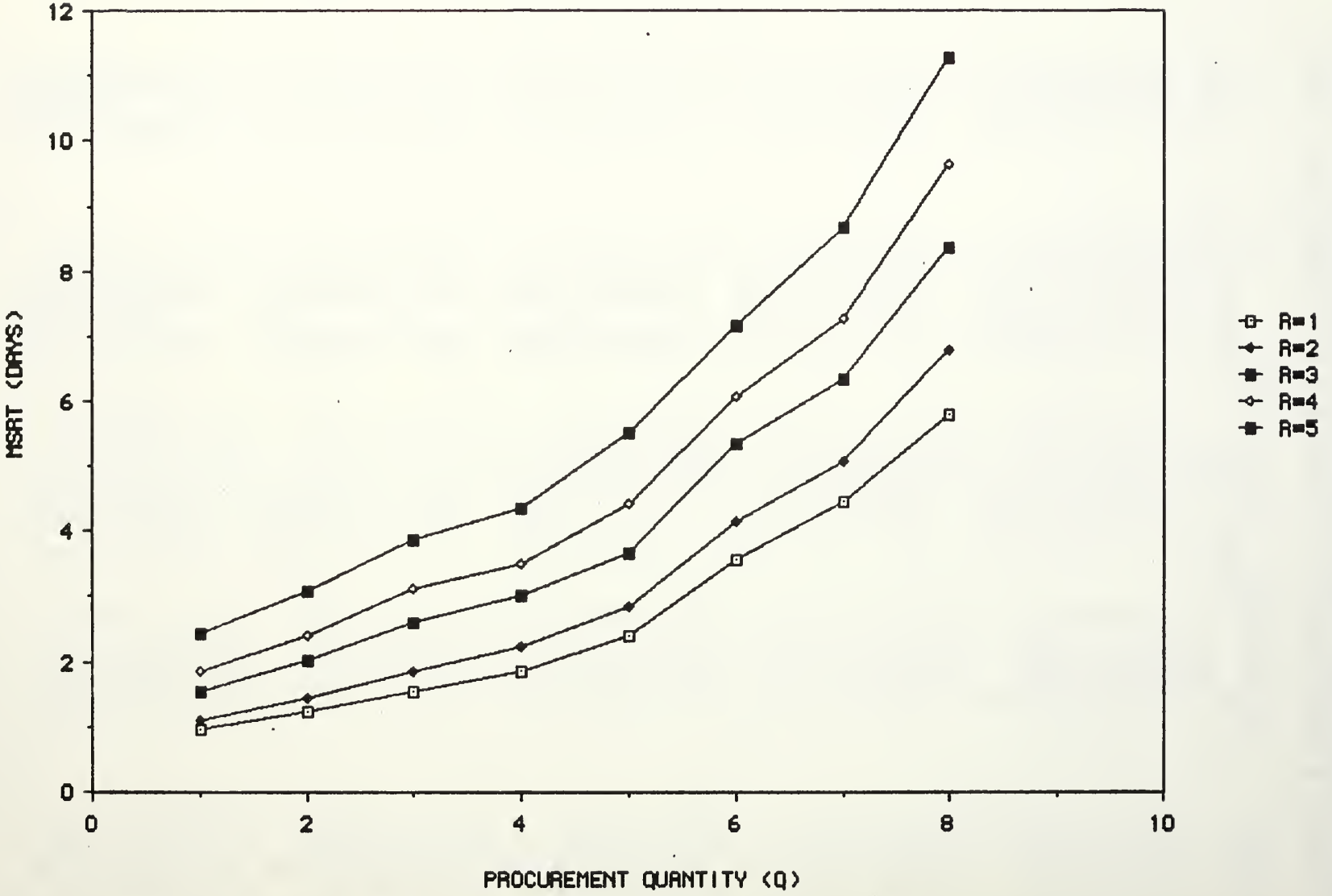

Figure 5.6 Simulated MSRT as a Function of Procurement Quantity

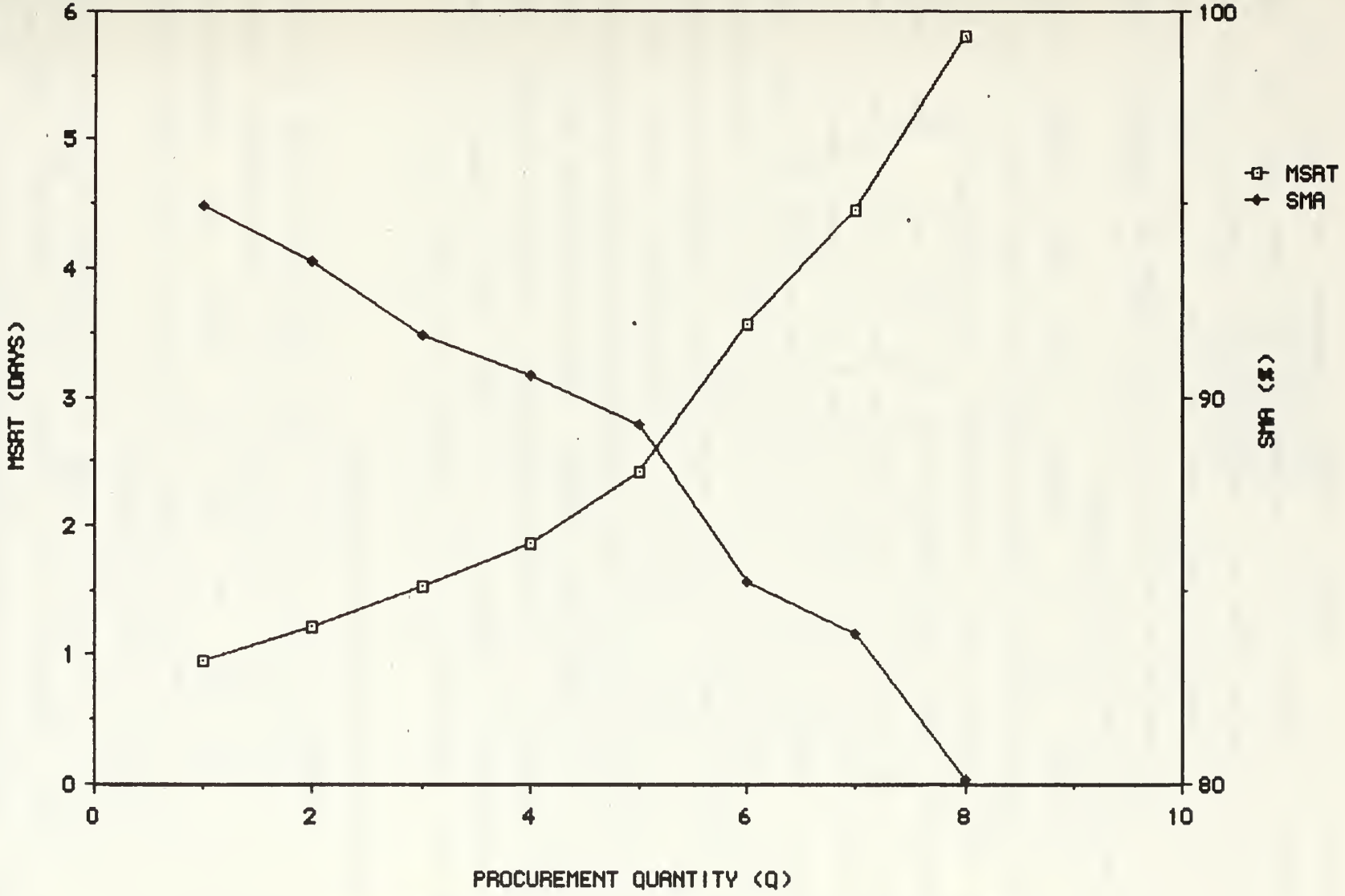

Figure 5.7 Simulated MSRT and SMA as a Function of Q when R=1

decreases in a roughly linear fashion as values for Q increase. SMA does not decrease at the same rate that MSRT increases because SMA only considers the number of backorders and not the average length of time that a backorder exists. This is the primary reason for using MSRT as opposed to SMA to measure system performance.

Referring now to Figure 5.8, this graph shows corresponding MSRT and ADDDR values for three runs in which Q was held constant and R was varied. The bottom plots in the respective MSRT and ADDDR groups are for Q=1. The middle plots in each group are for Q=5 and the top plots are for Q=8 (Q=8 data was not included in Table 5.1). Note here that, as expected, ADDDR increases in proportion to MSRT for each pair of plots. This is due to the fact that MSRT is a function of the total backorder time experienced during the resupply cycle, or more precisely, time-weighted units short. Additionally, note the large increase between the Q=5 and Q=8 plots for both MSRT and ADDDR. When the value for Q was changed from 5 to 8, MSRT increased by over 100 percent for all corresponding values of R. ADDDR for the same Q values increased approximately 35 percent as R varied from 1 to 9.

E. RECURRING INVENTORY PATTERNS

A secondary objective of the simulation runs was to identify any recurring patterns in the repairables cycle. Graphical analysis was used to detect any discernable patterns as the amount of data outputted to the events files was too large to screen visually.

Twenty-five simulation runs were plotted in conjunction with other analyses and screened for obvious patterns. Sample outputs are contained in Figures 5.9 and 5.10. Input

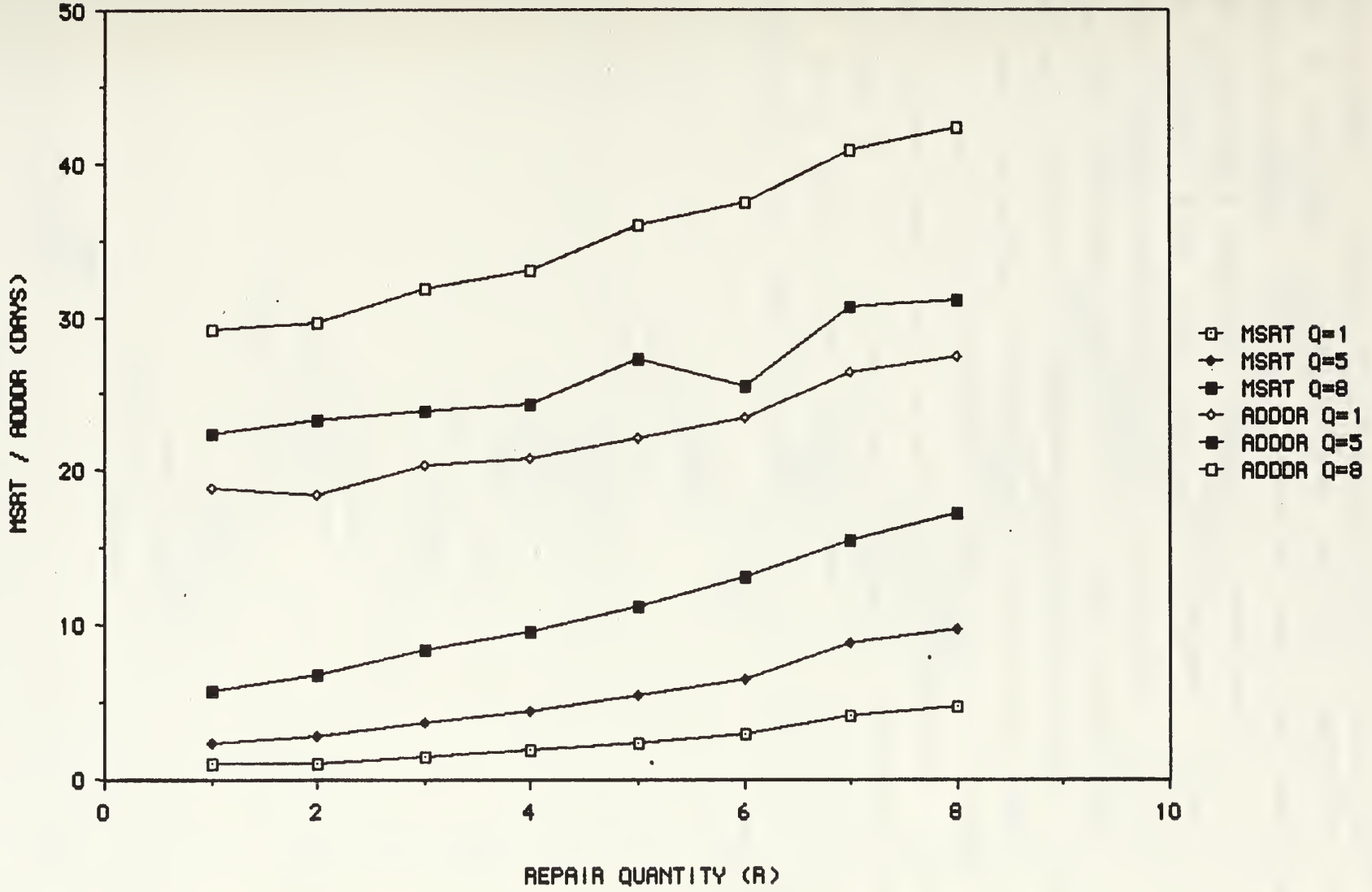

Figure 5.8 Simulated MSRT and ADDDR as a Function of R

parameters are indicated on the two graphs. None of the plots generated contained any consistant patterns in the repairables cycle once the model simulation approached steady state (i.e. procurement and repair pipelines filled and RFI units being returned to stock from both repair and procurement). As noted in Section B of this chapter, there are a significant number of situations in which the large number of units in both the procurement and repair pipelines at the same time results in a period of prolonged stockouts. In Figure 5.9, a prolonged stockout situation occurs during year 20. In Figure 5.10, stockouts occur almost continuously from the middle of year 10 through year 13. It is important to note that the on hand inventory never returns to SW as there are always units in both the repair and procurement pipelines.

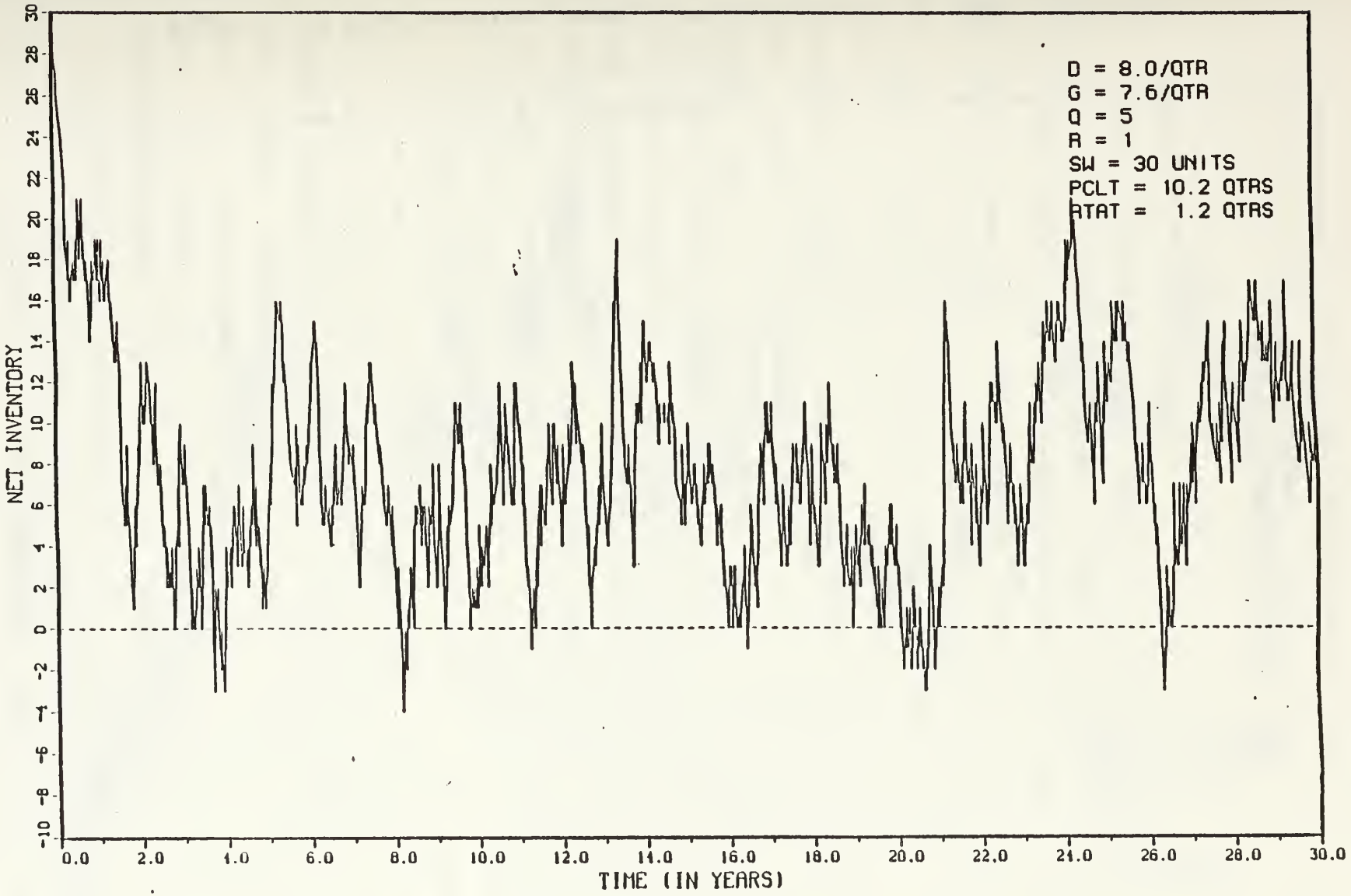

Figure 5.9 Simulated Net Inventory as a Function of Time - Plot No. 1

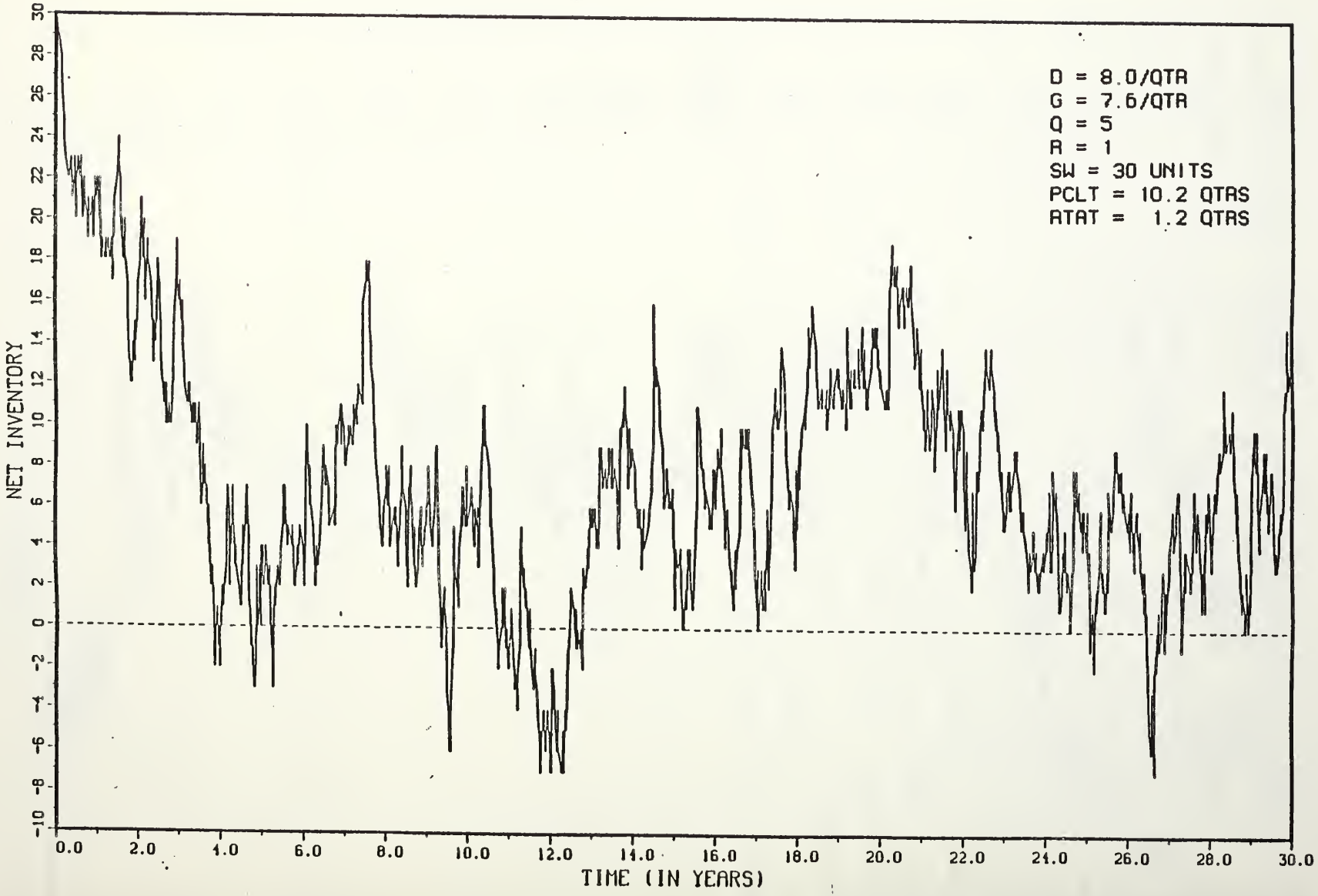

Figure 5.10 Simulated Net Inventory as a Function of Time - Plot No. 2

VI. SUMMARY AND CONCLUSIONS

A. SUMMARY

Chapter II provided an overview of the Navy Supply System including discussions on the Navy logistics organization, the Navy Stock Fund, the repairables system and supply system performance measures. This chapter served as a prelude for the detailed presentation of the current and proposed wholesale repairables inventory models in Chapter III. In Chapter III, we discussed the resupply cycle and reviewed the underlying mathematical theory for the proposed wholesale level model as originally presented by Apple [Ref.8] and Gormly [Ref.9]. The proposed model is fundamentally different from the current model in that it directly relates resources to operational readiness by determining the minimum total investment in wholesale inventory required to meet a specified mean supply response time (MSRT) goal. As such, this model is consistent with the DOD's and CNO's established policy objectives for supply system performance as outlined in OPNAVINST 4441.12B [Ref.12]. Furthermore, the proposed model provides for a smooth transition from the Navy's new wholesale initial provisioning model. In contrast, the current repairables model, which attempts to minimize the total annual costs associated with supply system operations, does not consider total investment levels or MSRT. Neither does it provide for an easy transition from the new provisioning model.

In Chapter IV, results of the initial performance comparison tests between the two models using actual inventory management data were presented. These tests showed

that the proposed model consistently requires less investment in wholesale system stock to achieve the same MSRT goal attained with the present model using the same input parameters. These tests also demonstrated that by reducing the lot sizes for procurement (Q) and repair (R), significant savings in total investment level could be realized without affecting supply response time or system material availability.

Chapter V discussed the results of supplemental research conducted on the proposed model using a single item inventory simulation. Inventory simulations served to increase our understanding of the dynamics of the repairables inventory system and verify the theoretical performance of the new model. We were able to identify the conditions which lead to the occurrence of stockouts and isolate the probability distributions for demands occurring during procurement lead time and repair turnaround time using the assumptions for the proposed model. Sensitivity analysis conducted using simulation provided additional insight into the effects of increases in procurement and repair lot sizes on MSRT and SMA.

B. CONCLUSIONS

Although the proposed model still requires additional testing to better understand the effects of changes in procurement and repair lot size policies, the initial performance tests have demonstrated that this model is capable of out-performing the current model by a sufficiently large margin to merit serious consideration for implementation at the Navy's inventory control points. While it can be argued that the proposed model is too simplistic in that it does not consider many of the costs associated with

supply system operations, we as military logistics managers must always be receptive to new ideas which have the potential to improve overall supply system efficiency and responsiveness without tieing up scarce financial resources in unneeded inventory. By considering the relative costs and benefits associated with stocking an entire inventory of items, the proposed model attempts to optimize system performance as a whole without having a significant impact on other system costs associated with ordering and holding stock. In fact, it can be argued that the proposed model provides inventory managers with increased flexibility to control other system costs by keeping them independent of the levels computation process.

First of all, the proposed model provides the flexibility to select Q and R values to take advantage of economical lot size procurements and repairs and in consideration of ICP workload and other constraints. Secondly, the proposed model avoids the need to indirectly quantify unknown backorder/stockout costs as the MSRT goal controls the extent of backorders directly. Thirdly, by minimizing the total amount of stock required at the wholesale level, holding costs as computed in the current model will also be reduced. Finally, and most importantly, the aggregate MSRT goal, as an input parameter for the proposed model, can be set to meet established objectives for any new weapon system's operational availability.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

There are four major areas in which additional research should be conducted to gain a better understanding of the dynamics of the proposed model and the repairables system.

As already indicated, additional tests must be conducted to provide a better understanding of the effects of procurement workload constraints and ordering policies on investment levels and the MSRT goal. As it has already been demonstrated that the proposed repairables model can outperform the current UICP model using the UICP determined Q and R quantities, additional research should concentrate on evaluating the cost savings obtainable through quantity discount buys against the increase in investment level for wholesale stock. The Q-Star program currently being evaluated at SPCC would provide a convenient mechanism for analyzing these cost tradeoffs for the proposed model.

Secondly, additional research should be conducted to determine appropriate MSRT goals for the wholesale level. As has already been suggested by both Gormly [Ref.9] and Pearsall [Ref.10], setting MSRT goals by IMEC category appears to the logical approach to this problem, but additional analysis is required to determine what these goals should be.

Thirdly, as the single item model simulation proved to be of significant value in increasing our knowledge of the dynamics of the repairables system and the resupply cycle, work in this area should continue on a larger scale. The initial results from goodness of fit tests conducted on sample distributions for demands occurring during procurement lead time and repair turnaround time failed to confirm the assumption that the probability distribution for demand during the resupply cycle follows the Poisson distribution. Additional research using simulations is required to identify the resulting probability distributions and understand the changes that occur in them as attrition rates increase and Q and R values are varied. It is also recommended that a

multi-item simulation be programmed to evaluate overall model performance and analyze the effects of procurement workload and other constraints.

Finally, as the proposed repairables model is easily converted to a consumables model, performance tests should also be conducted against the current UICP consumables model using actual inventory data. If results from these tests are favorable, consideration should also be given to implementing the proposed model as the new wholesale level consumables model. This would provide a single model for both consumables and repairables.

APPENDIX A

```
C ***********************************************************************
C *** PROGRAM TO TEST PROPOSED WHOLESALE REPAIRABLES REPLENISHMENT   ***
C *** MODEL AGAINST THE CURRENT UICP INTEGRATED REPAIRABLES MODEL    ***
C ***********************************************************************
C *** MAIN PROGRAM
      REAL*8 NAME2(3)/'MIN INVE','STMENT L','EVEL'/
      REAL*8 NAME3(3)/'MIN MSRT',' ',' '/
      REAL*8 NAME1(3)/'UICP INT','EG. REPA','IRABLES'/
      REAL Q1/'1   '/,Q2/'4D  '/,Q3/'EOQ '/,Q4/'D   '/,Q5/'UICP'/
      REAL RQ1/'1   '/,RQ2/'4D  '/,RQ3/'EOQ '/,RQ4/'D   '/,RQ5/'UICP'/
      INTEGER STOP(1000),MARK(1000),LOT(1000),MD,PBP,RLC
      INTEGER X(1000),NSO(1000),QMIN(1000),NRPR(1000)
      INTEGER NPO,NOPT,N,NN,NI
      REAL D(1000),G(1000),PCLT(1000),RTAT(1000),LAM,SLC(1000)
      REAL H,Z(1000),T(1000),Q(1000),QQ(1000)
      REAL CT(1000),C1(1000),C2(1000),COG1(1000),COG2(1000),RSR(1000)
      REAL A2(1000),DMAD(1000),RF(1000),C11(1000),E(1000),RMIN,RMAX
      REAL RVAR(1000),DRTAT(1000),TOV(2),QR(1000),QRI(1000),QRR(1000)
      REAL MODMST,MODNSF,MSRTG(10),MSRTGG,PVAR(1000)
      REAL QQR(1000),AS1(1000),CRT,COGG1,COGG2
      REAL BB(10),QM,QMR
      REAL*8 B
      COMMON SN(1000,9)
      EXTERNAL MODMST,MODNSF
C *** THE NEXT PARAMETER MUST BE SPECIFIED WHENEVER A NEW COG IS
C *** INTRODUCED. THIS NUMBER IS PROVIDED BY THE PRINTOUT FROM
C *** REPDATA PROGRAM WHICH ESTABLISHES A TEMPORARY DATA SET ON MVS004.
      N=39
C *** THE NEXT NUMBER SPECIFIES FULL TABLE LISTING(NPO=0) OR ONLY
C *** A SUMMARY (NPO=1).
      NPO=1
C *** THE VALUES OF THE PROCUREMENT AND REPAIR QUANTITIES MUST BE
C *** SELECTED. PROGRAM PARAMETERS ARE SET TO CORRESPOND TO THE DESIRED
C *** QUANTITIES. THE PROGRAM PARAMETERS AND VALUES ARE: MQ=1 FOR Q=1,
C *** R=1, MQ=2 FOR Q=QUICP,R=RUICP. ALSO PARAMETERS QM AND QMR MUST BE
C *** SET; QM=Q1 OR Q2, AND QMR=RQ1 OR RQ2.
      MQ=5
      QM=Q5
      QMR=RQ5
C *** THE APPROPRIATE MODEL MUST BE SELECTED. NOPT=1 IS MIN INVESTMENT
C *** LEVEL AND NOPT=2 IS MIN MSRT. THE TESTS REPORTED HERE USED NOPT=1
C *** ONLY. NN IS THE NUMBER OF MEASURES OF PERFORMANCE; IF MSRT AND
C *** SMA ARE BOTH USED THEN NN=2.
      NOPT=1
```

```
      NN=2
C *** CRT IS THE CARCASS RETURN TIME FROM CUSTOMER TO DEPOT. IT IS NOT
C *** NOT PART OF CARES DATA. GORMLY ESTIMATE AS OF 1/12/87 IS 40 DAYS.
      CRT=40./91.
C *** THE ANNUAL HOLDING COST FOR REPAIRABLES IS 21¢ PER DOLLAR HELD.
      H=0.21
C *** NI IS A COUNT OF VIABLE ITEMS (NOT HAVING STRANGE DATA).
      NI=0
C *** THE FOUR-DIGIT GOG PARAMETERS ARE READ. THEN EACH ITEM'S DATA IS
C *** READ. THE NOTATION IS THE ICP STANDARD USED IN VARIOUS DOCUMENTS.
    1 READ(10,2)RMIN,RMAX,LAM,PBP,RLC
    2 FORMAT(4X,2F4.2,F7.0,I2,I1)
      DO 23 I=1,N
   22 READ(10,898,END=24)COG1(I),COG2(I),MARK(I),(SN(I,J),J=1,9),SLC(I),
     *E(I),PCLT(I),RSR(I),RTAT(I),NRPR(I),C1(I),C11(I),D(I),G(I),
     *PVAR(I),RF(I),AS1(I),RVAR(I),DRTAT(I),
     *C2(I),A2(I),DMAD(I),LOT(I),NSO(I),QMIN(I)
  898 FORMAT(2A2,I1,9A1,A1,F3.3,F4.2,F3.2,F4.2,I4,6F10.2,F8.0,3F10.2,
     *F8.2,F10.2,2I8,I5)
C *** THE FOLLOWING STATEMENTS ARE SCREENS TO ELIMINATE STRANGE DATA.
      IF(D(I).EQ.250000.)GO TO 22
      IF(D(I).EQ.0.0)GO TO 22
      IF(C2(I).LE.5.0)GO TO 22
      IF(G(I).EQ.0.0)GO TO 22
      IF(D(I).LT.G(I))GO TO 22
      IF(PVAR(I).EQ.0.0)GO TO 22
      IF(RVAR(I).EQ.0.0)GO TO 22
      IF(LOT(I).NE.0)GO TO 22
      NI=NI+1
   23 CONTINUE
   24 WRITE(6,444)NI
  444 FORMAT(4X,'NI=',I8)
      COGG1=COG1(1)
      COGG2=COG2(1)
C *** THE PPV VALUE IS COMPUTED FOR EACH ITEM.
      DO 5 I=1,NI
         CT(I)=CRT
         STOP(I)=0
         T(I)=RTAT(I) + CT(I)
         IF(D(I).LE.G(I))GO TO 3
         Z(I)=(D(I)-G(I))*PCLT(I) + G(I)*T(I)
         GO TO 4
    3    Z(I)=D(I)*T(I)
    4    IF(PVAR(I).GT.Z(I))PVAR(I)=Z(I)
    5 CONTINUE
      MSRTGG=0.0
C *** THE CURRENT ICP MODEL IS CALLED TO PROVIDE THE BASIS FOR THE
```

```
C *** TESTS. THIS MODEL PROVIDES THE GOAL MSRT VALUE, THE UICP VALUES
C *** FOR Q AND R, AND THE MAXIMUM INVENTORY POSITION AND INVESTMENT
C *** FOR EACH ITEM FOR THE ICP MODEL.
      CALL ICPMOD(NI,H,B,X,Z,RTAT,C1,C11,C2,D,G,QQ,NRPR,RF,PVAR,LOT,
     *DMAD,E,LAM,MARK,PBP,SLC,RMIN,RMAX,RLC,NSO,COGG1,AS1,A2,QRI,QQR)
C *** THE PERFORMANCE OF THE ICP MODEL IS COMPUTED AND PRINTED.
      CALL PRTOUT(1,NAME1,QM,B,QQ,QRI,QQR,N,NI,NN,X,Z,C11,D,G,MSRTGG,
     *COGG1,COGG2,NPO,TOV,QMR)
      MOD=1
C *** THE PROPOSED MODEL'S GOAL IS COMPUTED.
      MSRTGG=TOV(2)
C *** THE VALUES OF THE PROPOSED MODEL'S Q AND R (QRR) ARE ESTABLISHED.
C *** THE EXPECTED ORDER QUANTITY ,QR, IS ALSO COMPUTED.
      DO 40 I=1,NI
         Q(I)=1.0
         IF(MQ.EQ.2)Q(I)=QQ(I)
         QRR(I)=1.0
         IF(QMR.EQ.RQ2)QRR(I)=QRI(I)
         QR(I)=Q(I)*(1.-G(I)/D(I))+QRR(I)*(G(I)/D(I))
   40 CONTINUE
      MOD=2
C *** THE PROPOSED MODEL IS CALLED AND EACH ITEM'S MAX INVENTORY
C *** POSITION IS COMPUTED VIA MARGINAL ANALYSIS.
      CALL MODOPT(NI,NN,B,MODNSF,X,Z,D,QR,C11,STOP,MSRTGG,MOD)
C *** THE PERFORMANCE OF THE PROPOSED MODEL IS COMPUTED AND PRINTED.
      CALL PRTOUT(2,NAME2,QM,B,Q,QRR,QR,N,NI,NN,X,Z,C11,D,G,MSRTGG,
     *COGG1,COGG2,NPO,TOV,QMR)
 1000 CONTINUE
   99 STOP
      END
C
C *** ROUTINE TO FIND MIN X SUCH THAT CDF(X).GE.(1-RISK)
      INTEGER FUNCTION NFX(ZZ,PVAR,RISK,PBP,MARK)
      REAL ZZ,R,RISK,TT,PVAR
      INTEGER NX,NB,MARK,PBP
      BP=FLOAT(PBP)
      R=1.-RISK
      NX=0
C *** IF(MARK.EQ.0)GO TO 10**** MARK 0 IS IGNORED FOR REPAIRABLES.
      IF(ZZ.GE.BP)GO TO 12
      IF(ZZ.LT.BP)GO TO 11
   10 CALL CDFP(ZZ,NX,P,C,CC)
      IF(C.GE.R) GO TO 20
      NX=NX+1
      GO TO 10
   11 CALL CDFB(ZZ,NX,PVAR,C,NB)
      IF(NB.EQ.1)GO TO 12
```

```
      IF(C.GE.R)GO TO 20
      NX=NX+1
      GO TO 11
   20 NFX=NX
      RETURN
   12 CALL CDFN(R,TT)
      NFX=ZZ+TT*SQRT(PVAR)+0.9999
      RETURN
      END
C
C *** ROUTINE TO CALCULATE POISSON CDF AND MASS
C *** CUMULATIVE POISSON DISTRIBUTION
      SUBROUTINE CDFP(ZZ,K,P,C,D)
      REAL*8 ZZZ,PP,CC,CC1,DD
      REAL ZZ,P,C,D
      INTEGER K,I
      IF(K.LT.0)GO TO 12
      ZZZ=ZZ
      PP=DEXP(-ZZZ)
      CC=PP
      CC1=0.0
      IF(K.EQ.0) GO TO 11
      KK=5*IFIX(ZZ+0.5)
      IF(ZZ.GT.10.0.AND.K.GT.KK)GO TO 15
      DO 10 I=1,K
      CC1=CC
      PP=PP*ZZZ/DFLOAT(I)
      CC=CC+PP
   10 CONTINUE
   11 P=PP
      C=CC
      DD=1.0-CC1
      D=DD
      RETURN
  12  P=0.0
      C=0.0
      D=1.0
      RETURN
  15  P=0.0
      C=1.0
      D=0.0
      RETURN
      END
C
C *** ROUTINE TO CALCULATE NEGBINOMIAL CDF
      SUBROUTINE CDFB(ZZ,K,PVAR,C,NB)
      REAL ZZ,C,PVAR
```

```
      REAL*8 ZZZ,PP,CC,BR,R,BK,S22,B,BQ
      INTEGER K,I,NB
      NB=0
      ZZZ=ZZ
      S22=PVAR
      BR=ZZZ/S22
      BQ=S22/ZZZ
      IF(BQ.LE.1.0)GO TO 8
      R = 1.0-BR
      BK=(ZZZ**2)/(S22-ZZZ)
      IF(BK*DLOG(BQ).GT.9.0)GO TO 8
      PP=BR**BK
      CC=PP
      IF(K .EQ. 0) GO TO 11
      GO TO 9
    8 NB=1
      RETURN
    9 DO 10 I=1,K
      B=DFLOAT(I-1)
      PP=PP*R*(B+BK)/DFLOAT(I)
      CC=CC+PP
   10 CONTINUE
   11 C=CC
      RETURN
      END
C
C *** ROUTINE TO CALCULATE NORMAL DEVIATE GIVEN R.
      SUBROUTINE CDFN(R,TT)
      INTEGER IER
      REAL R,TT
      CALL MDNRIS(R,TT,IER)
      RETURN
      END
C
C *** THE CURRENT ICP INTEGRATED REPAIRABLES MODEL
C *** THIS SUBROUTINE COMPUTES ONLY THE PROCUREMENT Q AND ROP.
      SUBROUTINE ICPMOD(N,H,B,X,Z,RTAT,C1,C11,C2,D,G,Q,NRPR,RF,PVAR,LOT,
     *DMAD,E,LAM,MARK,PBP,SLC,RMIN,RMAX,RLC,NSO,COG,AS1,A2,QR,QQR)
      INTEGER N,X(N),NRPR(N),LOT(N),MARK(N),Y(1000),R121,Q8,Q9
      INTEGER ROP(1000),NSO(N),RLC,PBP,Q22,Q21,Q2C,QS
      REAL Z(N),C1(N),C2(N),D(N),G(N),RF(N),PVAR(N),DMAD(N),AS1(N)
      REAL SL(1000),RMIN,RMAX,C3(1000),RISK(1000),E(N),SLC(N),H
      REAL Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q(N),COG,LAM,R,R11,R12,R13,R1,C11(N)
      REAL QQR(N),QR(N),A2(N),AA,AC,QR1,RRCT,QR2,QR3,QSL
      REAL*8 B
      REAL A7/'7R'/
      B=0.0
```

```
C *** DETERMINE THE PROCUREMENT REORDER POINT.
      DO 5 I=1,N
         IF(D(I).LE.G(I))GO TO 3
         IF(LOT(I).NE.0.AND.Z(I).LE.0.0)GO TO 2
         C3(I)=C2(I)*(G(I)/D(I)) + C1(I)*(1. -(G(I)/D(I)))
         RISK(I)=H*C3(I)*D(I)/(H*C3(I)*D(I) + E(I)*LAM*RF(I))
         RISK(I)=AMIN1(RISK(I),RMAX)
         RISK(I)=AMAX1(RISK(I),RMIN)
         Y(I)=NFX(Z(I),PVAR(I),RISK(I),PBP,MARK(I))
         R121=MAX0(Y(I),NRPR(I))
         R12=FLOAT(R121)
         CALL SHFLIF(SL(I),SLC(I))
         IF(SL(I).EQ.100.)R11=R12
         IF(SL(I).EQ.100.)GO TO 1
         R11=4.*(D(I)-G(I))*SL(I) + Z(I) - (D(I)-G(I))*4.
   1     R13=33.*D(I)+Z(I)
         R1=AMIN1(R11,R12,R13)
         R=AMAX1(R1,FLOAT(NSO(I)),Z(I))
         ROP(I)=IFIX(R+0.999)
         GO TO 5
   2     ROP(I)=0
         GO TO 5
   3     ROP(I)=IFIX(Z(I)+0.999)
   5  CONTINUE
C *** COMPUTE PROCUREMENT QUANTITY NEXT.
      DO 12 I=1,N
         IF(LOT(I).NE.0)GO TO 10
         IF(D(I).LE.G(I))GO TO 9
         Q1=SQRT(8.*(D(I)-G(I))*(1970.+AS1(I))/(H*C1(I)))
         IF(COG.NE.A7)GO TO 7
         Q1=SQRT(8.*(D(I)-G(I))*(1530.+AS1(I))/(H*C1(I)))
    7    Q2=4.*(D(I)-G(I))
         Q3=AMAX1(Q1,Q2)
         Q4=12.*(D(I)-G(I))
         Q5=AMIN1(Q3,Q4)
         IF(SL(I).EQ.100.)Q6=Q5
         IF(SL(I).EQ.100.)GO TO 8
         Q6=4.*(D(I)-G(I))*SL(I)-AMAX1(0.,(FLOAT(ROP(I))-Z(I)))
   8     Q7=AMIN1(Q5,Q6)
         Q8=IFIX(Q7+0.999)
         Q9=MAX0(1,Q8)
         Q(I)=FLOAT(Q9)
         GO TO 11
   9     Q(I)=1.0
         GO TO 11
  10     Q(I)=FLOAT(LOT(I))
  11     IF(Q(I).LT.1.0)Q(I)=1.0
```

```
C *** COMPUTE CONSTRAINED REPAIR QTY (B021A=Q2C)FOR THE ICP MODEL.
        AC=660.
        IF(COGG1.EQ.A7)AC=133.
        IF(C2(I).EQ.0.0)QR(I)=0.0
        IF(C2(I).EQ.0.0)GO TO 20
        QR1=SQRT(8.*(AC+A2(I))*G(I)/(H*C2(I)))
        RRCT=0.0
        IF(COGG1.EQ.A7)RRCT=0.08
        QR2=RRCT*G(I)
        QR3=AMAX1(1.,QR1,QR2)
        Q22=IFIX(QR3+0.999)
        CALL SHFLIF(SL(I),SLC(I))
        QSL=4.*D(I)*SL(I)-AMAX1(0.0,(FLOAT(Y(I))-Z(I)))
        QS=IFIX(QSL+0.999)
        Q21=MIN0(Q22,QS)
        Q2C=MAX0(1,Q21)
        QR(I)=FLOAT(Q2C)
  20    IF(QR(I).EQ.0.0)GO TO 21
C *** THE EXPECTED ORDER QUANTITY IS COMPUTED.
        QQR(I)=Q(I)*(1.-G(I)/D(I))+QR(I)*(G(I)/D(I))
        GO TO 22
  21    QQR(I)=Q(I)
C *** THE INVENTORY POSITION AND INVESTMENT COST IS COMPUTED.
  22    X(I)=ROP(I)+IFIX(QQR(I)+0.5)
        B=B+C11(I)*FLOAT(X(I))
  12  CONTINUE
      RETURN
      END
C
C *** THE SHELF LIFE CODE IS CONVERTED TO THE COMPUTATIONAL FACTOR.
      SUBROUTINE SHFLIF(SL,SLC)
      REAL*4 A/'A   '/,B/'B   '/,C/'C   '/,D/'D   '/,E/'E   '/,
     *F/'F   '/,
     *G/'G   '/,H/'H   '/,J/'J   '/,K/'K   '/,L/'L   '/,M/'M   '/,
     *N/'N   '/,P/'P   '/,Q/'Q   '/,R/'R   '/,X/'X   '/,S/'S   '/,
     *A1/'1   '/,A2/'2   '/,A3/'3   '/,A4/'4   '/,A5/'5   '/,
     *A6/'6   '/,A7/'7   '/,A8/'8   '/,A9/'9   '/,A0/'0   '/
      REAL*4 SL,SLC
      IF(SLC.EQ.A0)SL=100.
      IF(SLC.EQ.A0)GO TO 50
      IF(SLC.EQ.A)SL=1./3.
      IF(SLC.EQ.A)GO TO 50
      IF(SLC.EQ.B)SL=2./3.
      IF(SLC.EQ.B)GO TO 50
      IF(SLC.EQ.C.OR.SLC.EQ.A1)SL=3./3.
      IF(SLC.EQ.C.OR.SLC.EQ.A1)GO TO 50
      IF(SLC.EQ.D)SL=4./3.
```

```
      IF(SLC.EQ.D)GO TO 50
      IF(SLC.EQ.E)SL=5./3.
      IF(SLC.EQ.E)GO TO 50
      IF(SLC.EQ.F.OR.SLC.EQ.A2)SL=6./3.
      IF(SLC.EQ.F.OR.SLC.EQ.A2)GO TO 50
      IF(SLC.EQ.G.OR.SLC.EQ.A3)SL=9./3.
      IF(SLC.EQ.G.OR.SLC.EQ.A3)GO TO 50
      IF(SLC.EQ.H.OR.SLC.EQ.A4)SL=12./3.
      IF(SLC.EQ.H.OR.SLC.EQ.A4)GO TO 50
      IF(SLC.EQ.J)SL=15./3.
      IF(SLC.EQ.J)GO TO 50
      IF(SLC.EQ.K.OR.SLC.EQ.A5)SL=18./3.
      IF(SLC.EQ.K.OR.SLC.EQ.A5)GO TO 50
      IF(SLC.EQ.L)SL=21./3.
      IF(SLC.EQ.L)GO TO 50
      IF(SLC.EQ.M.OR.SLC.EQ.A6)SL=24./3.
      IF(SLC.EQ.M.OR.SLC.EQ.A6)GO TO 50
      IF(SLC.EQ.N)SL=27./3.
      IF(SLC.EQ.N)GO TO 50
      IF(SLC.EQ.P)SL=30./3.
      IF(SLC.EQ.P)GO TO 50
      IF(SLC.EQ.Q.OR.SLC.EQ.A7)SL=36./3.
      IF(SLC.EQ.Q.OR.SLC.EQ.A7)GO TO 50
      IF(SLC.EQ.R.OR.SLC.EQ.A8)SL=48./3.
      IF(SLC.EQ.R.OR.SLC.EQ.A8)GO TO 50
      IF(SLC.EQ.S.OR.SLC.EQ.A9)SL=60./3.
      IF(SLC.EQ.S.OR.SLC.EQ.A9)GO TO 50
      SL=100.
   50 RETURN
      END
C
C *** THE PROPOSED MODEL'S ALGORITHM
      SUBROUTINE MODOPT(N,NN,B,AMODEL,X,ZN,D,QR,C1,STOP,GOALG,MOD)
C *** PERFORM OPTIMAL ALLOCATION FOR GIVEN MODEL USING
C *** MARGINAL ANALYSIS METHOD AND LOWER BOUNDING.
C *** N=NO. ITEMS
C *** B=INVESTMENT LEVEL OF STOCK FUND
C *** AMODEL=ENTRY POINT FOR MODEL TO USE (STANDARDIZED ARGUMENTS)
C *** X=OPTIMAL ALLOCATIONS PER ITEM
C *** ZN= MEAN DEMAND DURING RESUPPLY TIME OR PPV
C *** C1=PROCUREMENT COST FOR EACH ITEM
C *** RR=WORK VECTOR TO STORE RATIOS
      INTEGER N,I,K,MK,STEP,X(N),STOP(N)
      REAL ZN(N),QR(N),D(N),MR,RR(1000),SR,TRY
      REAL MODNSF,MODMST,C1(N),GOALG
      REAL*8 B
      SR=0.
```

```
      KK=1
C *** INITIALIZE
      B=0.
      DO 11 I=1,N
         X(I)=0
C *** INITIALIZE STOP BEFORE OPTIMIZING ON INVESTMENT LEVEL(STOP=1 MEANS
C *** THAT THE LEVEL HAS HIT THE ITEM MSRT BOUND).
         STOP(I)=0
         RR(I)=AMODEL(ZN(I),D(I),QR(I),C1(I),X(I)+1,STOP(I))
   11 CONTINUE
   12 STEP=0
C *** DO UNTIL MSRT OR BUDGET GOAL IS REACHED
   20 CONTINUE
      STEP=STEP+1
      MK=0
      MR=10000000.
      IF(MOD.EQ.3)MR=0.
      DO 30 K=1,N
          IF(STOP(K).EQ.1)GO TO 30
          IF(RR(K).GE.MR)GO TO 30
          MR=RR(K)
          MK=K
   30 CONTINUE
      IF(MK .EQ. 0) GO TO 40
C *** ALLOCATE ONE MORE UNIT OF ITEM MK IF POSSIBLE.
      B=B+C1(MK)
      X(MK)=X(MK)+1
C *** NEXT CHECK TO SEE IF GOAL HAS BEEN ATTAINED.
      CALL GOALM(X,N,ZN,D,QR,TRY,GOALG)
      IF(TRY.EQ.0.0)GO TO 40
      SR=MR
      RR(MK)=AMODEL(ZN(MK),D(MK),QR(MK),C1(MK),X(MK)+1,STOP(MK))
      GO TO 20
   40 RETURN
      END
C
C *** ROUTINE TO MINIMIZE INVESTMENT LEVEL OF STOCK FUND
      REAL FUNCTION MODNSF(ZZ,D,QR,C,K,STOP)
C *** COMPUTE MARGIN ANALYSIS RATIOS ASSUMING
C *** POISSON DEMAND.
      REAL ZZ,QR,D,C,MSRT,MSRTD,TS1,TS2
      INTEGER K,STOP
      IF(ZZ.NE.0.0)GO TO 10
      MODNSF=0.0
      MSRT=-0.0001
      GO TO 12
   10 TS1=TWUS(ZZ,QR,K-1)
```

```
      TS2=TWUS(ZZ,QR,K)
      IF(TS1.EQ.TS2)GO TO 13
      MODNSF= C/(TS1-TS2)
      MSRT=TS2/D
   12 MSRTD=91.*MSRT
      IF(MSRTD.LT.0.001)STOP=1
      GO TO 15
   13 MODNSF=C
   15 RETURN
      END
C
C *** ROUTINE TO CALCULATE THE EXP TIME WTD UNITS SHORT FOR K UNITS
      REAL FUNCTION TWUS(ZZ,QR,K)
      REAL ZZ,P1,P2,SW,RP,QR,P3,P4,P5,P6,CD1,CD2,CD3,CD4,CD5,CD6
      REAL CCD1,CCD2,CCD3,CCD4,CCD5,CCD6,BETA1,BETA2
      REAL*8 PHI1,PHI2,DCD1,DCD2,D1,D2,T1,T2,Z,DBETA1,DBETA2
      INTEGER K
      SW=FLOAT(K)
      Z=ZZ
      RP=SW-QR
      KRP=K-IFIX(QR+.5)
      IF(ZZ.GE.20.)GO TO 20
      CALL CDFP(ZZ,KRP-1,P1,CD1,CCD1)
      CALL CDFP(ZZ,KRP,P2,CD2,CCD2)
      CALL CDFP(ZZ,KRP+1,P3,CD3,CCD3)
      CALL CDFP(ZZ,K-1,P4,CD4,CCD4)
      CALL CDFP(ZZ,K,P5,CD5,CCD5)
      CALL CDFP(ZZ,K+1,P6,CD6,CCD6)
      IF (CCD1.LT.0.000001) GO TO 10
      BETA1=(CCD1*ZZ**2)/2.-CCD2*ZZ*KRP+CCD3*KRP*(KRP+1)/2.
      IF(BETA1.LT.0.000001)BETA1=0.0
      IF (CCD4.GE.0.000001) GO TO 7
      BETA2=0.0
      GO TO 8
    7 BETA2=(CCD4*ZZ**2)/2.-CCD5*ZZ*K+CCD6*K*(K+1)/2.
      IF(BETA2.LT.0.000001)BETA2=0.0
    8 TWUS=(BETA1-BETA2)/QR
      RETURN
   10 TWUS=0.0
      RETURN
   20 S=FLOAT(K)+0.5
      T1=(RP-ZZ)/SQRT(ZZ)
      IF(DABS(T1).LE.7.)GO TO 21
      PHI1=0.0
      IF(T1.GT.7.)D1=0.0
      IF(T1.LT.(-7.0))D1=1.0
      GO TO 22
```

```
   21 PHI1=(DEXP(-(T1**2)/2.))/SQRT(2.*3.14159265)
      CALL MDNORD(T1,CD1)
      D1=1.0-CD1
   22 DBETA1=Z*(D1*(1.0+T1**2)-T1*PHI1)/2.
      T2=(SW-ZZ)/SQRT(ZZ)
      IF(DABS(T2).LE.7.)GO TO 23
      PHI2=0.0
      IF(T2.GT.7.0)D2=0.0
      IF(T2.LT.(-7.0))D2=1.0
      GO TO 25
   23 PHI2=(DEXP(-(T2**2)/2.))/SQRT(2.*3.14159265)
      CALL MDNORD(T2,CD2)
      D2=1.0-CD2
   25 DBETA2=Z*(D2*(1.0+T2**2)-T2*PHI2)/2.
      TWUS=(DBETA1-DBETA2)/QR
      RETURN
      END
C
C *** ROUTINE TO SEE IF GOAL HAS BEEN ATTAINED.
      SUBROUTINE GOALM(X,N,Z,D,QR,TRY,MSRTG)
      INTEGER N,X(N),XI
      REAL Z(N),VO(1000),TV,SLT,D(N),QR(N),MSRTG,TRY
      REAL MSRTC,MSRT
      TV=0.0
      SLT=0.
      DO 10 I=1,N
         IF(Z(I).EQ.0.0)GO TO 16
         XI=X(I)
         SLT = SLT + D(I)
   14    MSRTC=TWUS(Z(I),QR(I),XI)/D(I)
         MSRT=AMAX1(MSRTC,0.0)
         GO TO 18
   16    MSRT=0.0
   18    VO(I) = 91.*MSRT
         TV = TV + VO(I)*D(I)
   10 CONTINUE
      TV=TV/SLT
      TRY = 1.0
      IF(TV.LE.MSRTG)TRY = 0.0
   22 RETURN
      END
C
C *** ROUTINE TO EVALUATE PERFORMANCE AND PRINT OUT RESULTS
      SUBROUTINE PRTOUT(MD,NAME,QM,B,Q,QRR,QR,NT,N,NN,X,Z,C1,D,G,MSRTG,
     *COG1,COG2,NPO,TOV,QMR)
      INTEGER X(N),ROP(1000),NPO,NT
      REAL Z(N),OV(2,1000),TOV(2),C1(N),MSRTG,BSW(1000)
```

```
      REAL COG1,COG2,Q(N),D(N),G(N),QRR(N),QR(N)
      REAL*8 B,NAME(3)
      COMMON SN(1000,9)
      DO 1 I=1,N
      BSW(I)=C1(I)*X(I)
    1 ROP(I)=X(I)-IFIX(QR(I)+0.5)
C *** THE PERFORMANCE ROUTINE IS CALLED NEXT.
      CALL OBJECT(X,N,NN,Z,D,QR,OV,TOV)
      WRITE(6,900)
  900 FORMAT('1',///,'  ********************************************',
     *'************************************************************',
     *'***************')
      WRITE(6,901)MD,NAME,COG1,COG2,MSRTG,QM,QMR
  901 FORMAT('0',1X,' MODEL (',I1,')',2X,3A8,2X,'COG: ',2A2,8X,
     *'MSRT GOAL:',F8.2,' DAYS',4X,'QP: ',A4,4X,'QR:',A4)
C *** IF ONLY A SUMMARY TABLE IS DESIRED SKIP TO STATEMENT 907.
      IF(NPO.EQ.1)GO TO 907
      WRITE(6,902)
  902 FORMAT('0',5X,'NIIN',7X,'DEPTH',5X,'MSRT(DAYS)',4X,
     *'INVEST. LVL.',3X,'UNIT COST',6X,'QP',6X,
     *'ROP',6X,'PPV',9X,'D',9X,'G',9X,'QR')
      WRITE(6,903)((SN(I,J),J=1,9),X(I),OV(2,I),BSW(I),C1(I),Q(I),
     *ROP(I),Z(I),D(I),G(I),QRR(I),I=1,N)
  903 FORMAT(3X,9A1,2X,I8,2X,F12.3,5X,F12.2,2X,F10.2,2X,F7.2,I8,2X,
     *F10.3,F10.3,F10.3,F10.3)
  906 WRITE(6,904)TOV(2),B,TOV(1)
  904 FORMAT('0',4X,'OVERALL PERFORMANCE:',2X,F9.3,4X,'$',F12.2,5X,
     *'SMA:',F8.2)
      GO TO 909
  907 WRITE(6,908)TOV(2),B,TOV(1),NT,N
  908 FORMAT('0',4X,'OVERALL PERFORMANCE:',2X,F9.3,4X,'$',F12.2,5X,
     *'SMA:',F8.2,4X,'N/NI=',I8,'/',I8)
  909 WRITE(6,905)
  905 FORMAT('0',' ****************************************************',
     *'************************************************************',
     *'***********')
      RETURN
      END
C
C *** ROUTINE TO COMPUTE THE MSRT AND SMA VALUES FOR A GIVEN ALLOCATION.
      SUBROUTINE OBJECT(X,N,NN,Z,D,QR,OV,TOV)
      INTEGER N,NN,X(N),XI
      REAL Z(N),OV(NN,N),TOV(NN),SLT,MSRT,OV1,D(N),QR(N)
      REAL CD,P,MSRTC,BO,BOT,DD
      TOV(1)=0.
      TOV(2)=0.
      BO=0.0
```

```
      BOT=0.0
    5 CONTINUE
      SLT=0.
      DO 10 I=1,N
          IF(Z(I).EQ.0.0)GO TO 6
          XI=X(I)
          SLT = SLT + D(I)
          OV(1,I)=0.
C *** THE EXPECTED NUMBER OF BACKORDERS IS COMPUTED.
          CALL EBO(Z(I),XI,D(I),QR(I),OV1)
          MSRTC=TWUS(Z(I),QR(I),XI)/D(I)
          MSRT=AMAX1(MSRTC,0.0)
          OV(1,I)=AMIN1(OV1,1.0)
          GO TO 7
    6     OV(1,I)=0.0
          MSRT=1.0
    7     OV(2,I) = 91.*MSRT
          TOV(2) = TOV(2) + OV(2,I)*D(I)
          BO=BO+OV(1,I)
   10 CONTINUE
      IF(SLT.EQ.0.0)SLT=1.0
      BOT=BO/SLT
      TOV(1)= (1.-BOT)*100.
      TOV(2)=TOV(2)/SLT
      RETURN
      END
C
C *** THE ROUTINE TO COMPUTE THE EXPECTED NUMBER OF BACKORDERS.
      SUBROUTINE EBO(Z,X,D,QR,OV1)
      REAL Z,D,QR,OV1,ALPHA1,ALPHA2,X1,X2,CD1,CD2,CDD1,CDD2,P1,P2
      REAL PP1,PP2,PHI1,PHI2
      INTEGER X
      K1=X-IFIX(QR+0.5)
      X1=FLOAT(K1)
      X2=FLOAT(X)
      K2=IFIX(X2)
      IF(Z.GT.20.)GO TO 10
      CALL CDFP(Z,K1,P1,CD1,D1)
      CALL CDFP(Z,K2,P2,CD2,D2)
      ALPHA1=D1*(Z-X1)+X1*P1
      ALPHA2=D2*(Z-X2)+X2*P2
      IF(ALPHA1.LT.0.0)ALPHA1=0.0
      IF(ALPHA2.LT.0.0)ALPHA2=0.0
      GO TO 20
   10 T1=(X1-Z)/SQRT(Z)
      IF(ABS(T1).GT.7.0)GO TO 12
      PHI1=(EXP(-(T1**2)/2.))/SQRT(2.*3.14159265)
```

```
      CALL MDNOR(T1,CD1)
      D1=1.0-CD1
      GO TO 13
   12 IF(T1.GT.7.0)D1=0.0
      IF(T1.LT.(-7.0))D1=1.0
      PHI1=0.0
   13 T2=(X2-Z)/SQRT(Z)
      IF(ABS(T2).GT.7.0)GO TO 14
      PHI2=(EXP(-(T2**2)/2.))/SQRT(2.*3.14159265)
      CALL MDNOR(T2,CD2)
      D2=1.0-CD2
      GO TO 15
   14 IF(T2.GT.7.0)D2=0.0
      IF(T2.LT.(-7.0))D2=1.0
      PHI2=0.0
   15 ALPHA1=(PHI1-T1*D1)*(SQRT(Z))
      ALPHA2=(PHI2-T2*D2)*(SQRT(Z))
      IF(ALPHA1.LT.0.0)ALPHA1=0.0
      IF(ALPHA2.LT.0.0)ALPHA2=0.0
   20 OV1=(ALPHA1-ALPHA2)*D/QR
      RETURN
      END
```

APPENDIX B

VARIABLES LISTING FOR REPAIRABLES SIMULATION

D	:	QUARTERLY DEMAND RATE
G	:	QUARTERLY REGENERATION RATE
Q	:	PROCUREMENT ORDER QUANTITY
R	:	REPAIR ORDER QUANTITY
SW	:	WHOLESALE STOCK LEVEL
ROP	:	PROCUREMENT REORDER POINT
PLT	:	PROCUREMENT LEAD TIME (IN QUARTERS)
TAT	:	REPAIR TURNAROUND TIME (IN QUARTERS)
PCLT	:	PROCUREMENT LEAD TIME (IN DAYS)
RTAT	:	REPAIR TURNAROUND TIME (IN DAYS)
RSR	:	REPAIR SURVIVAL RATE
CRR	:	CARCASS RETURN RATE
IP	:	INVENTORY POSITION
RGR	:	CARCASS REGENERATION RATE
RFI	:	READY FOR ISSUE UNITS ON-HAND
NRFI	:	NOT READY FOR ISSUE UNITS ON-HAND
PCMT	:	UNITS IN PROCUREMENT
REP	:	UNITS IN REPAIR
DEF	:	ATTRITIONS OCCURRING SINCE LAST PROCUREMENT ORDER
BO	:	OUTSTANDING BACKORDERS
AT	:	TOTAL NUMBER OF ATTRITIONS FOR SIMULATION
TR	:	TOTAL NUMBER OF CARCASSES INDUCTED FOR REPAIR
TRQN	:	TOTAL NUMBER OF DEMANDS FOR SIMULATION
TREP	:	TOTAL NUMBER OF REPAIR BATCHES INDUCTED
TBUY	:	TOTAL NUMBER OF PROCUREMENT ORDERS PLACED
BOT	:	INDIVIDUAL BACKORDER TIMES
TBOT	:	TOTAL BACKORDER TIME FOR SIMULATION
ABO	:	AVERAGE NUMBER OF BACKORDERS PER YEAR
AREP	:	AVERAGE NUBER OF UNITS REPAIRED PER YEAR
ABUY	:	AVERAGE NUMBER OF UNITS PURCHASED PER YEAR
MSRT	:	COMPUTED MEAN SUPPLY RESPONSE TIME
ADDBO	:	AVERAGE DAYS DELAY FOR BACKORDERED REQUISITIONS
SMA	:	COMPUTED SYSTEM MATERIAL AVAILABILITY
NYRS	:	NUMBER OF YEARS USED FOR SIMULATION
POPT	:	REPORT PRINTOUT OPTION
CLK	:	SIMULATION CLOCK
TIME	:	TIME BETWEEN DEMANDS
RTIME	:	REPAIR BATCH INDUCTION TIMES
PTIME	:	PROCUREMENT ORDER PLACEMENT TIMES
BTIME	:	BACKORDER START TIMES
QQ	:	NUMBER OF UNITS IN A PROCUREMENT BATCH
RR	:	NUMBER OF REPAIRABLE CARCASSES IN A REPAIR BATCH
DRQ	:	NUMBER OF DEMANDS OCCURRING PRIOR TO AN ATTRITION DEMAND
DRQ	:	NUMBER OF DEMANDS OCCURRING PRIOR TO A REPAIR DEMAND

```
DQ      :       DRQ OR DPQ FOR DORCT SUBROUTINE
RQ      :       NUMBER OF UNITS INDUCTED IN A REPAIR BATCH
AQ      :       ATTRITIONS OCCURRING AT DOP
BQ      :       NUMBER OF BACKORDERS FILLED BY A REPAIR OR PROCUREMENT
DRSTR   :       DEMANDS OCCURING DURING REPAIR CYCLES
DRSTP   :       DEMANDS OCCURING DURING PROCUREMENT CYCLES
DRST    :       DEMANDS OCCURING DURING THE RESUPPLY CYCLE
C       :       CARCASS RETURN ATTRITION GENERATOR (RANDOM NUMBERS)
E       :       REPAIR ATTRITION GENERATOR (RANDOM NUMBERS)
Y       :       NUMBER OF REPAIR BATCHES OUTSTANDING
Z       :       NUMBER OF PROCUREMENT ORDERS OUTSTANDING
X       :       DORCT SELECTION INDEX
I       :       VARIABLE INDEX
J       :       CLOCK INDEX
K       :       REPAIR INDEX
L       :       PROCUREMENT INDEX
M       :       BACKORDER INDEX
N       :       STORAGE ARRAY INDEX
NN      :       STORAGE ARRAY INDEX
IK      :       DEMAND DURING REPAIR INDEX
IL      :       DEMAND DURING PROCUREMENT INDEX
JK      :       REPAIR ATTRITION INDEX
NBO     :       BACKORDER INDEX
```

APPENDIX C

PROGRAM LISTING FOR REPAIRABLES SIMULATION

```
C     ************************************************************************
C     ************************************************************************
C     **     SIMULATION OF WHOLESALE REPAIRABLES REPLENISHMENT          **
C     **     INVENTORY MODEL WITH POISSON DEMANDS (SINGLE ITEM)         **
C     ************************************************************************
C     ************************************************************************
C
C***  VARIABLE DECLARATIONS  ********************************************
      INTEGER C(1500),E(1500),IP(2500),RFI(2500),NRFI(2500),TR/0/,
     *DEF(2500),PCMT(2500),REP(2500),BO(2500),Q,R,SW,ROP,POPT,I,TRQN/0/,
     *IX,J/1/,M/1/,N/2500/,NN/1500/,NYRS,TREP/0/,TBUY/0/
      REAL CLK(2500),TIME(1500),D,G,PLT,RTAT,CRR,RSR,PCLT,TAT,RGR,
     *BOT(1500),TOUT
C***  SPECIFY INPUT PARAMETERS  *****************************************
      D=8.0
      G=6.8
      PCLT=10.2
      TAT=1.2
      RSR=1.0
      SW=30
      R=2
C     Q=1
      Q=IFIX(4*(D-G)+.99)
C***  SELECT NUMBER OF YEARS FOR SIMULATION (1-30) **********************
      NYRS=30
C***  SELECT PRINTOUT OPTION (POPT=0 FOR SHORT, POPT=1 FOR LONG AND ****
C***  POPT = 2 FOR NET INVENTORY PLOT ***********************************
      POPT=1
C***  SELECT INITIAL SEED FOR RANDOM NUMBER GENERATOR  ******************
C***  (ANY INTEGER BETWEEN 1 AND 2**31-1)  ******************************
      IX=4448855
      TOUT=NYRS*364.0
      RGR=G/D
      CRR=RGR/RSR
      PLT=PCLT*91.
      RTAT=TAT*91.
C***  GENERATE TIME BETWEEN DEMANDS,CARCASS RETURNS AND REPAIR SURVIVALS
      CALL RANDOM(TIME,CRR,RSR,C,D,E,NN,IX)
C***  INITIALIZE STORAGE ARRAYS  ****************************************
      DO 10 I=1,N
           IP(I)=0
           RFI(I)=0
           NRFI(I)=0
           DEF(I)=0
```

```
          PCMT(I)=0
          REP(I)=0
          BO(I)=0
          CLK(I)=0.
 10   CONTINUE
      DO 20 I=1,MN
          BOT(I)=0.
 20   CONTINUE
C***  PERFORM SIMULATION  ************************************************
      CALL EVENT(CLK,TIME,BOT,IP,RFI,NRFI,DEF,PCMT,REP,BO,PLT,RTAT,AT,
     *TR,C,D,E,G,Q,R,SW,ROP,J,M,N,MN,TOUT,TRQN,TREP,TBUY)
C***  PRINT OUT RESULTS  *************************************************
      CALL PRINT(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,Q,R,SW,ROP,D,G,CRR,
     *RSR,RGR,PCLT,TAT,BOT,POPT,TRQN,TREP,TBUY,NYRS,J,M,N,MN,AT,TR)
      STOP
      END
C
C     ******************************************************************
C     *   ROUTINE TO GENERATE RANDOM DEMANDS, CARCASS RETURNS AND      *
C     *   REPAIR SURVIVALS USING THE LLRANII RANDOM NUMBER GENERATOR   *
C     ******************************************************************
C
      SUBROUTINE RANDOM(TIME,CRR,RSR,C,D,E,N,IX)
      INTEGER C(N),E(N),CC(1500),ZZ(1500),W,X,IX,N,MUL,ISORT
      REAL TIME(N),A(1500),B(1500),T(1500),Z(1500),CRR,RSR,D
C***  SELECT MULTIPLIER FOR RANDOM RANDOM NUMBER GENERATOR  ************
C***  (MUL=1 FOR 16807 OR MUL=2 FOR 397204094)
      MUL=1
C***  SPECIFY SORT OPTION (0 FOR NO SORT OR 1 FOR ASCENDING ORDER SORT)
      ISORT=0
C***  GENERATE TIME BETWEEN DEMANDS  *************************************
      CALL SRND(IX,A,N,MUL,ISORT)
      DO=91.0/D
      DO 10 I=1,N
          T(I)=ABS(LOG(A(I))*DO)
          IF(I.EQ.1)THEN
              TIME(I)=T(I)
          ELSE
              TIME(I)=TIME(I-1)+T(I)
          ENDIF
 10   CONTINUE
C***  GENERATE CARCASS RETURN RATES  *************************************
      CALL SRND(IX,B,N,MUL,ISORT)
      W=IFIX(CRR*1000+0.5)
      DO 20 I=1,N
          B(I)=B(I)*1000.
          CC(I)=IFIX(B(I)+0.5)
          IF(CC(I).LT.W)THEN
              C(I)=0
          ELSE
              C(I)=1
          ENDIF
 20   CONTINUE
```

```
C***  GENERATE REPAIR SURVIVAL RATES  ***********************************
      CALL SRND(IX,Z,N,MUL,ISORT)
      X=IFIX(RSR*1000+0.5)
      DO 30 I=1,N
           Z(I)=Z(I)*1000.
           ZZ(I)=IFIX(Z(I)+0.5)
           IF(ZZ(I).LT.X)THEN
                E(I)=1
           ELSE
                E(I)=0
           ENDIF
 30   CONTINUE
      RETURN
      END
C
C     ***************************************************************
C     *            ROUTINE TO MANAGE SIMULATION EVENTS              *
C     ***************************************************************
C
      SUBROUTINE EVENT(CLK,TIME,BOT,IPX,RFIX,NRFIX,DEFX,PCMTX,REPX,BOX,
     *PLT,RTAT,AT,TR,C,D,E,G,Q,R,SW,ROP,J,M,N,NN,TOUT,TRQN,TREP,TBUY)
      INTEGER C(NN),E(NN),IPX(N),RFIX(N),NRFIX(N),DEFX(N),BOX(N),TR,
     *PCMTX(N),REPX(N),IP,RFI,SW,Q,R,NRFI/0/,AT/0/,DEF/0/,PCMT/0/,
     *REP/0/,BO/0/,I,J,K/1/,L/1/,M,IK/0/,IL/0/,JK/1/,Y/0/,Z/0/,N,NN,
     *TRQN,TREP,TBUY,ROP,RR(1500),QQ(1500),DRQ(1500),DPQ(1500),
     *DRST(1500)
      REAL CLK(N),TIME(NN),RTIME(1500),PTIME(1500),BTIME(1500),BOT(NN),
     *PLT,RTAT,TOUT
C***  INITIALIZE  OPENING INVENTORY VALUES  ****************************
      IP=SW
      RFI=SW
      ROP=SW-Q
C***  INITIALIZE STORAGE ARRAYS*****************************************
      DO 10 I=1,NN
           BTIME(I)=0.0
           PTIME(I)=50000.
           RTIME(I)=50000.
           QQ(I)=0
           RR(I)=0
           DRQ(I)=0
           DPQ(I)=0
           DRST(I)=0
 10   CONTINUE
C***  STORE OPENING INVENTORY VALUES************************************
      CALL ARRAY(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,IPX,RFIX,NRFIX,DEFX,
     *PCMTX,REPX,BOX,J,N)
      DO 20 I=1,NN
 1      IF((TIME(I).GE.RTIME(K)).AND.(TIME(I).LT.PTIME(L)))THEN
          CALL RQUEIN(CLK,RTIME,BTIME,RFI,REP,BO,BOT,RR,I,J,K,M,N,NN,Y,
     *    DRQ,DRST)
          GO TO 2
        ELSE IF((TIME(I).GE.PTIME(L)).AND.(TIME(I).LT.RTIME(K)))THEN
```

```
          CALL PDUEIN(CLK,PTIME,BTIME,RFI,PCMT,BO,BOT,QQ,I,J,L,M,N,NN,Z,
     *    DPQ,DRST)
          GO TO 2
        ELSE IF((TIME(I).GE.RTIME(K)).AND.(PTIME(L).LE.RTIME(K)))THEN
          CALL PDUEIN(CLK,PTIME,BTIME,RFI,PCMT,BO,BOT,QQ,I,J,L,M,N,NN,Z,
     *    DPQ,DRST)
          GO TO 2
        ELSE IF((TIME(I).GE.PTIME(L)).AND.(RTIME(K).LE.PTIME(L)))THEN
          CALL RDUEIN(CLK,RTIME,BTIME,RFI,REP,BO,BOT,RR,I,J,K,M,N,NN,Y,
     *    DRQ,DRST)
          GO TO 2
        ELSE
          GO TO 3
        ENDIF
 2      CALL ARRAY(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,IPX,RFIX,NRFIX,
     *    DEFX,PCMTX,REPX,BOX,J,N)
        GO TO 1
 3      CALL DEMAND(CLK,TIME,RTIME,PTIME,BTIME,IP,RFI,NRFI,AT,DEF,PCMT,
     *    REP,BO,Q,R,RR,QQ,RTAT,PLT,C,E,I,J,K,L,M,N,NN,Y,Z,TR,DRQ,DPQ,
     *    IK,IL,JK)
        CALL ARRAY(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,IPX,RFIX,NRFIX,
     *          DEFX,PCMTX,REPX,BOX,J,N)
        IF(CLK(J).GE.TOUT)GO TO 99
 20     CONTINUE
 99     TRQN=I
        TREP=K*R-AT
        TBUY=AT-DEF
        RETURN
        END
C
C     ***************************************************************
C     *  ROUTINE TO RECORD DEMAND, CHECK FOR BACKORDER CONDITION,   *
C     *        AND INITIATE PROCUREMENT OR REPAIR ACTIONS           *
C     ***************************************************************
C
      SUBROUTINE DEMAND(CLK,TIME,RTIME,PTIME,BTIME,IP,RFI,NRFI,AT,DEF,
     *PCMT,REP,BO,Q,R,RR,QQ,RTAT,PLT,C,E,I,J,K,L,M,N,NN,Y,Z,TR,DRQ,DPQ,
     *IK,IL,JK)
      INTEGER IP,RFI,NRFI,AT,DEF,PCMT,REP,BO,I,K,L,M,N,Y,Z,C(NN),IK,IL,
     *NN,J,Q,R,RR(NN),E(NN),QQ(NN),DRQ(NN),DPQ(NN),TR,JK
      REAL CLK(N),TIME(NN),RTIME(NN),PTIME(NN),BTIME(NN),PLT,RTAT
      J=J+1
      CLK(J)=TIME(I)
C***  REGISTER DEMAND AND DETERMINE IF NRFI CARCASS WILL BE RETURNED  **
      IF(C(I).EQ.0)THEN
           NRFI=NRFI+1
           TR=TR+1
      ELSE
           AT=AT+1
           DEF=DEF+1
      ENDIF
      IF((C(I).EQ.0).AND.(NRFI.GE.1))THEN
           IK=IK+1
```

```
            DRQ(IK)=I
         ENDIF
         IP=IP-1
         RFI=RFI-1
C***     CHECK FOR BACKORDER CONDITION  ************************************
         IF(RFI.LT.0)THEN
C           RFI=0
            BTIME(M+BO)=TIME(I)
            BO=BO+1
         ENDIF
C***     INITIATE REPAIR ACTION IF SUFFICIENT NRFI UNITS ARE AVAILABLE  ***
         IF(NRFI.EQ.R)THEN
           CALL REPAIR(CLK,RTIME,IP,NRFI,AT,DEF,REP,E,J,K,R,RR,Y,RTAT,N,NN,
     *   JK)
         ENDIF
         IF((C(I).EQ.1).AND.(DEF.GE.1))THEN
            IL=IL+1
            DPQ(IL)=I
         ENDIF
C***     INITIATE REPROCUREMENT ACTION IF REORDER POINT HAS BEEN REACHED **
         IF(DEF.GE.Q)THEN
            CALL PROCMT(CLK,PTIME,IP,DEF,PCMT,PLT,QQ,J,L,N,NN,Z)
         ENDIF
         RETURN
         END
C
C     ************************************************************************
C     *                  ROUTINE TO INITIATE REPAIR ACTION                   *
C     ************************************************************************
C
         SUBROUTINE REPAIR(CLK,RTIME,IP,NRFI,AT,DEF,REP,E,J,K,R,RR,Y,RTAT,
     *N,NN,JK)
         INTEGER RR(NN),IP,NRFI,AT,DEF,REP,I,J,K,N,NN,E(NN),Y,R,AQ,RQ,JK
         REAL CLK(N),RTIME(NN),RTAT
         RQ=0
         DO 10 I=JK,JK+(R-1)
            RQ=RQ+E(I)
 10      CONTINUE
         NRFI=NRFI-R
         AQ=R-RQ
         REP=REP+RQ
         IP=IP+RQ
         RR(K+Y)=RQ
         RTIME(K+Y)=CLK(J)+RTAT
         IF(RQ.LT.R)THEN
            DEF=DEF+AQ
            IP=IP-AQ
            AT=AT+AQ
         ENDIF
         JK=JK+R
         Y=Y+1
         RETURN
         END
```

```
C
C     ***************************************************************
C     *          ROUTINE TO INITIATE REPROCUREMENT ACTION            *
C     ***************************************************************
C
      SUBROUTINE PROCMT(CLK,PTIME,IP,DEF,PCMT,PLT,QQ,J,L,N,NN,Z)
      INTEGER IP,DEF,PCMT,QQ(NN),J,L,N,NN,Z
      REAL CLK(N),PTIME(NN),PLT
      PCMT=PCMT+DEF
      IP=IP+DEF
      QQ(L+Z)=DEF
      PTIME(L+Z)=CLK(J)+PLT
      DEF=0
      Z=Z+1
      RETURN
      END
C
C     ***************************************************************
C     *        ROUTINE TO RECEIVE RFI UNITS FROM REPROCUREMENT       *
C     ***************************************************************
C
      SUBROUTINE PDUEIN(CLK,PTIME,BTIME,RFI,PCMT,BO,BOT,Q,I,J,L,M,N,NN,
     *Z,DPQ,DRST)
      INTEGER RFI,PCMT,BO,Q(NN),RQ,J,LL,M,N,NN,Z,DRST(NN),DPQ(NN),I,X
      REAL CLK(N),PTIME(NN),BTIME(NN),BOT(NN)
      X=1
      Z=Z-1
      J=J+1
10    CONTINUE
      CLK(J)=PTIME(L)
      PCMT=PCMT-Q(L)
      RFI=RFI+Q(L)
      RQ=Q(L)
C     CALL DDRCT(DRST,DPQ,RQ,I,X,NN)
C***  DETERMINE DISTRIBUTION OF RFI ASSETS ****************************
C***  DUE IN FROM PROCUREMENT (STOCK AND/OR UNFILLED ORDERS) **********
      IF(BO.GT.0)THEN
           CALL BKORDR(CLK,BTIME,BOT,RFI,BO,RQ,J,M,N,NN)
      ENDIF
      L=L+1
      RETURN
      END
C
C     ***************************************************************
C     *          ROUTINE TO RECEIVE REPAIRED UNITS FROM REPAIR       *
C     ***************************************************************
C
      SUBROUTINE RDUEIN(CLK,RTIME,BTIME,RFI,REP,BO,BOT,R,I,J,K,M,N,NN,Y,
     *DRQ,DRST)
      INTEGER RFI,REP,BO,R(NN),RQ,I,J,K,M,N,NN,Y,DRST(NN),DRQ(NN),X
      REAL CLK(N),RTIME(NN),BTIME(NN),BOT(NN)
      X=0
```

```
      Y=Y-1
      J=J+1
      CLK(J)=RTIME(K)
      REP=REP-R(K)
      RFI=RFI+R(K)
      RQ=R(K)
C     CALL DORCT(DRST,DRQ,RQ,I,X,NN)
C***  DETERMINE DISTRIBUTION OF RFI ASSETS ****************************
C***  DUE IN FROM REPAIR (STOCK AND/OR UNFILLED ORDERS)  **************
      IF(BO.GT.0)THEN
           CALL BKORDR(CLK,BTIME,BOT,RFI,BO,RQ,J,M,N,NN)
      ENDIF
      K=K+1
      RETURN
      END
C
C     ***************************************************************
C     *  ROUTINE TO DETERMINE DISTRIBUTION OF RFI ASSETS DUE IN FROM   *
C     *       REPAIR OR PROCUREMENT AND COMPUTE BACKORDER TIMES       *
C     ***************************************************************
C
      SUBROUTINE BKORDR(CLK,BTIME,BOT,RFI,BO,BQ,J,M,N,NN)
      INTEGER I,J,M,NBO,N,NN,BQ,RFI,BO
      REAL CLK(N),BTIME(NN),BOT(NN)
      IF(BO.LE.BQ)THEN
C          RFI=RFI-BO
           NBO=BO
           BO=0
      ELSE
           NBO=BQ
           BO=BO-BQ
C          RFI=0
      ENDIF
C***  COMPUTE LENGTH OF BACKORDER *************************************
      DO 10 I=M,M+(NBO-1)
           BOT(I)=CLK(J)-BTIME(I)
 10   CONTINUE
      M=M+NBO
      RETURN
      END
C
C     ***************************************************************
C     *      ROUTINE TO COMPUTE DEMAND DURING RESUPPLY CYCLE TIME     *
C     ***************************************************************
C
      SUBROUTINE DORCT(DRST,DQ,RQ,I,X,N)
      INTEGER DRST(N),DQ(N),I,J,K/1/,L,M/1/,RQ,DRSTR(1500),DRSTP(1500),
     *X,II/1/
      IF(X.EQ.0)THEN
           DO 10 J=K,K+(RQ-1)
                DRSTR(J)=(I-1)-DQ(J)
                DRST(II)=DRSTR(J)
      WRITE(6,34)DRST(II)
```

```
                II=II+1
 10         CONTINUE
            K=K+RQ
      ELSE
            DO 20 L=M,M+(RQ-1)
                DRSTP(L)=(I-1)-DQ(L)
                DRST(II)=DRSTP(L)
      WRITE(6,34)DRST(II)
                II=II+1
 20         CONTINUE
            M=M+RQ
      ENDIF
 34   FORMAT(2X,I4)
      RETURN
      END
C
C     ******************************************************************
C     *              ROUTINE TO STORE INDIVIDUAL EVENTS                *
C     ******************************************************************
C
      SUBROUTINE ARRAY(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,IPX,RFIX,NRFIX,
     *DEFX,PCMTX,REPX,BOX,I,N)
      INTEGER IPX(N),RFIX(N),NRFIX(N),DEFX(N),PCMTX(N),REPX(N),
     *BOX(N),IP,RFI,NRFI,AT,DEF,PCMT,REP,BO,I,N
      REAL CLK(N)
      IPX(I)=IP
      RFIX(I)=RFI
      NRFIX(I)=NRFI
      DEFX(I)=DEF
      PCMTX(I)=PCMT
      REPX(I)=REP
      BOX(I)=BO
      RETURN
      END
C
C     ******************************************************************
C     * ROUTINE TO COMPUTE PERFORMANCE STATISTICS AND PRINTOUT RESULTS *
C     ******************************************************************
C
      SUBROUTINE PRINT(CLK,IP,RFI,NRFI,DEF,PCMT,REP,BO,Q,R,SW,ROP,D,G,
     *CRR,RSR,RGR,PLT,RTAT,BOT,POPT,TRQN,TREP,TBUY,NYRS,J,M,N,NN,AT,TR)
      INTEGER IP(N),RFI(N),NRFI(N),DEF(N),PCMT(N),REP(N),BO(N),Q,
     *R,SW,ROP,I,J,NYRS,TRQN,TREP,TBUY,M,N,NN,AT,TR,POPT,X
      REAL CLK(N),BOT(NN),CRR,RSR,RGR,PLT,RTAT,D,G,MSRT,ADDBO,ARQN,SMA,
     *ABO,TBOT,AREP,ABUY
      IF(POPT.EQ.2)GO TO 55
C***  COMPUTE TOTAL BACKORDER TIME FOR SIMULATION PERIOD  **************
      TBOT=0
      IF(M.EQ.0)THEN
            TBOT=0.0
            MSRT=0.0
            ADDBO=0.0
            SMA=100.0
```

```
          ABO=0
      ELSE
          DO 30 I=1,M
              TBOT=TBOT+BOT(I)
30        CONTINUE
          MSRT=TBOT/TRQN
          ADOBO=TBOT/M
          SMA=100.*(1.0-FLOAT(M)/TRQN)
          ABO=FLOAT(M)/NYRS
      ENDIF
      ARQN=FLOAT(TRQN)/NYRS
      AREP=FLOAT(TREP)/NYRS
      ABUY=FLOAT(TBUY)/NYRS
      WRITE(6,1)D,G,SW,ROP,Q,R
      WRITE(6,2)PLT,RTAT,CRR,RSR,RGR
      IF(POPT.EQ.0)GO TO 50
      WRITE(6,11)
      WRITE(6,9)
      WRITE(6,3)
      WRITE(6,4)
      WRITE(6,9)
55    DO 10 I=1,J
          IF(POPT.EQ.2)THEN
              CLK(I)=CLK(I)/364.
              WRITE(6,5)CLK(I),IP(I),RFI(I)
          ELSE
              WRITE(6,12)CLK(I),IP(I),RFI(I),NRFI(I),DEF(I),REP(I),
     *        PCMT(I),BO(I)
          ENDIF
10    CONTINUE
      IF(POPT.EQ.2)THEN
          GO TO 88
      ENDIF
      WRITE(6,9)
      WRITE(6,11)
50    WRITE(6,6)ARQN,ABO
      WRITE(6,7)AREP,ABUY
      WRITE(6,8)SMA,MSRT,ADOBO
      WRITE(6,11)
      WRITE(6,9)
 1    FORMAT(2X,'D:',F6.2,' QTRS',3X,'G:',F6.2,' QTRS',4X,'SW:',I4,4X,
     *'ROP:',I4,4X,'Q:',I4,4X,'R:',I4)
 2    FORMAT(2X,'PCLT:',F6.2,' QTRS',3X,'RTAT:',F6.2,' QTRS',3X,'CRR:',
     *F6.2,2X,'RSR:',F6.2,2X,'RGR:',F6.2)
 3    FORMAT(14X,'INV POS',8X,'O/H NRFI',8X,'IN REPAIR',7X,
     *'BACKORDERS')
 4    FORMAT(5X,'DAY',14X,'O/H RFI',9X,'DEFICIT',8X,'ON ORDER')
 5    FORMAT(F8.2,I4,I4)
12    FORMAT(2X,F8.2,4X,I4,4X,I4,4X,I4,4X,I4,4X,I4,4X,I4,4X,I4,4X,I4)
 6    FORMAT(2X,'AVG. NO. OF DEMANDS/YR:',F7.2,9X,
     *'AVG. NO. OF BACKORDERS/YR:',F7.2)
 7    FORMAT(2X,'AVG. NO. OF REPAIRS/YR:',F7.2,9X,
```

```
     *'AVG. NO. OF BUYS/YEAR:',4X,F7.2)
  8   FORMAT(2X,'SMA:',F7.2,' %',9X,'MSRT:',F8.3,' DAYS',12X,
     *'ADD/BO:',F8.3,' DAYS')
  9   FORMAT(' ')
 11   FORMAT(1X,'*************************************************************',
     *'**************************')
 88   RETURN
      END
```

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